Deliverable 3.1- Flight test concept study

Report on conceptualization of demonstration flight tests series

Date: 25.06.2025

Author: Marlin Juchem, Simon Kirschler, Devaiah Nalianda, Christoph Todt, Alejandra Martin-Frias, Raimund Zopp, Larissa Houston
Organization: DLR, TUIFLY, FLIGHTKEYS

Funded by the European Union

The project has received funding from the European Union`s Horizon Europe research and innovation programme under the Grant Agreement no. 101192301.

Document Title

Grant Agreement	101192301
Call Topic	HORIZON-CL5-2024-D5-01-07
Type of action	HORIZON Research and Innovation Action
Project title	Advancing Aeronautics and Aerosol research to Accelerate Climate neutral aviation
Project acronym	A4CLIMATE
Project start and end date	01.02.2025 – 31.01.2029
Duration	48 months
Work Package	3
Deliverable number	3.1
Due Date	31 July 2025
Submission date	30 July 2025
Author(s)	Marlin Juchem, Simon Kirschler, Devaiah Nalianda, Christoph Todt, Alejandra Martin-Frias, Raimund Zopp, Larissa Houston
Lead Beneficiary	Deutsches Zentrum für Luft - und Raumfahrt EV (DLR)
Reviewer(s)	Vincent de Haes, To70; Rogier Hendriks, To70; Jan van Manen, To70; Christiane Voigt, DLR

About the document

This report outlines a conceptual approach for contrail avoidance flights, aiming to identify operational strategies that minimize aviation's non-CO_2 climate impact—particularly the formation of persistent contrails and contrail cirrus. The objectives include improving scientific understanding of contrail formation conditions, evaluating the climate effectiveness of tactical avoidance, and assessing the feasibility of implementation within existing flight planning systems.

Document revision history

Version	Issue & Date	Internal Auditor	Name, Beneficiary short name	Date of approval
1	26 June 2025	WP leader	Larissa Houston, FKY	30 June 2025
2	03 July 2025	Coordinator	Christiane Voigt, DLR	29 July 2025
2	03 July 2025	Internal Review	Vincent de Haes, To70; Rogier Hendriks, To70; and Jan van Manen, To70	14 July 2025

Acknowledgment

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Nature of the deliverable [1]

Report

[1] Deliverable types:
R: document, report (excluding periodic and final reports).
DEM: demonstrator, pilot, prototype, plan designs.
DEC: websites, patent filings, press and media actions, videos, etc.

Dissemination level

PU	Public, fully open. e.g., website	X
SEN	Sensitive, limited under the conditions of the Grant Agreement	
CL	Classified information under the Commission Decision No2015/444	

Copyright notice

© A4CLIMATE

OTHER: software, technical diagrams, etc.

Table of contents

List of figures

Abbreviations

AKKL	*Arbeitskreis klimaneutrale Luftfahrt (*Working Group on Climate-Neutral Aviation)
ANSP	Air navigation service provider
ATC	Air Traffic Control
CoCIP	Contrail Cirrus Prediction model
Contrail	Condensation Trail
ISSR	Ice supersaturated region
NetCDF	Network Common Data From

Executive summary

This report presents the conceptual framework and detailed design of an upcoming multi-stakeholder flight trial aimed at reducing the climate impact of aviation-induced contrails. Building on recent scientific findings and operational insights, the trial design explores tactical rerouting strategies to avoid ice-supersaturated regions (ISSRs) where warming contrails form. The report outlines key methodological elements, including flights selection criteria, batching logic to target specific research and operational questions, and the integration of weather forecast and contrail prediction tools. It also addresses anticipated challenges related to air traffic management, evaluation strategies, and coordination across airlines, air navigation service providers, and research institutes.

The trial sets out to achieve three overarching goals:

1. Improve scientific understanding of contrail formation and the conditions that drive their climate impact.
2. Evaluate the effectiveness and operational feasibility of tactical contrail avoidance.
3. Develop practical guidance for integrating contrail mitigation into routine flight planning.

Approximately 400 test avoidance flights are planned, offering a critical opportunity to explore these objectives under real-world conditions. The ultimate aim is to assess the practical feasibility and scalability of contrail avoidance under operational constraints, laying the groundwork and blueprint for future implementation at scale.

1. Introduction

In an era of rapid global warming, the pinpointing of each contributing factor is increasingly vital to efforts aimed at reducing and mitigating the anthropogenic impact on Earth's climate (H. Lee et al., 2023). The aviation sector encompasses one of the largest economic activities worldwide and is forecasted to expand further within the upcoming decades ((ICAO, 2025; D. S. Lee et al., 2021). Besides emissions, including carbon dioxide (CO_2); nitrogen oxides (NO_x); water vapor; soot and sulfate aerosol (J. J. Lee et al., 2001), aviation also affects the climate through the formation of contrails (D. S. Lee et al., 2009; Schumann, 2005). Altogether, aviation accounts for approximately 4% of human-induced global warming (Klöwer et al., 2021; D. S. Lee et al., 2009), with estimates suggesting that more than half of this impact arises from non-CO_2 effects, such as contrails (D. S. Lee et al., 2021). As most mitigation scenarios project aviation to remain a net source of CO_2 emissions through mid-century (*Fit for 55 and ReFuelEU Aviation | EASA*, 2025; IEA (The International Energy Agency), 2025; Leipold et al., 2021; US Government, 2015), the significance of non-CO_2 effects in shaping the sector's climate impact is likely to increase – namely those related to contrail formation and their radiative forcing.

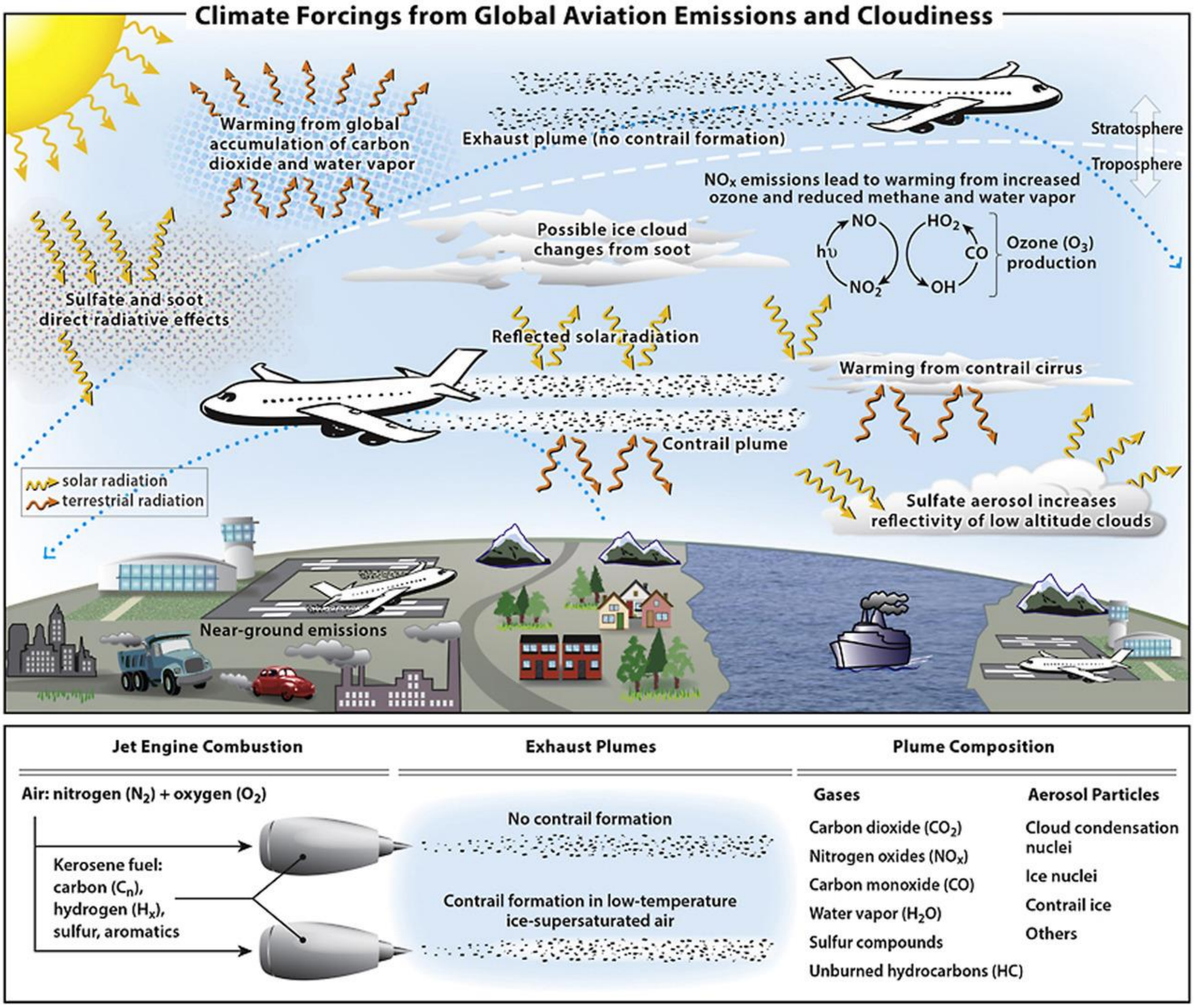

Figure 1: Simplified schematic of how aviation emissions and contrail cirrus affect climate. Aircraft release CO_2, NO_x, water vapor, soot, and sulfur compounds, which lead to both warming (e.g., CO_2, ozone, contrails) and cooling effects (e.g., sulfate aerosols). The overall impact is net warming due to positive radiative forcing (D. S. Lee et al., 2021).

Contrails, short for condensation trails, are jet-generated ice clouds that may appear as thin, linear streaks along flight paths in the upper troposphere, typically between 8 and 13 kilometers in altitude (Appleman, 1953; Schumann, 1996). Their formation, size and lifespan depend on interactions between aircraft engine exhaust and the cold ambient atmosphere (Schumann et al., 2012), mostly triggered by the combustion of aviation kerosene. The typical engine fuel burned in airplanes, being a hydrocarbon mixture, produces several combustion products. Of particular importance for contrail formation are the emissions of water vapor, heat and non-volatile particulate matter (nvPM), mainly soot, into the aircrafts wake (Appleman, 1953). As the exhaust is expelled into the cold, low-pressure environment, it undergoes rapid cooling, introduced by adiabatic expansion and turbulent mixing (Kärcher, 2018; Schumann, 2005). If the ambient atmosphere is already near supersaturation with respect to ice, the added water vapor can drive the local environment to a state of ice supersaturation (Appleman, 1953) - a condition that enables water vapor to condense and freeze onto available aerosol particles. During the early contrail formation stage (within 0.1 – 1 seconds) tiny, supercooled water droplets may initially form as the plume aerosols particles act as water condensation centers and compete for the surrounding water (Appleman, 1953). Once these droplets exist, the plume's high cooling rates lead to substantial ice nucleation, as the droplets dominantly freeze homogenously (Kärcher et al., 2015) and ice crystals may grow with decreasing temperatures. In contrast, heterogeneous freezing may occur on specific aerosol particles, mainly mineral dust, which catalyze ice formation at lower supersaturation and higher temperatures than required for homogeneous nucleation (Hoose & Möhler, 2012). The freezing scheme (homogeneous vs heterogeneous) plays a key role in determining the optical properties of contrail particles by influencing their size, habit orientation, and number-size distribution. Young contrails, primarily formed homogenously, have small ice particles (1-20 μm), which are smaller than typical cirrus particles. The shape and size of these particles may come closer to those of natural cirrus as the contrail formation ages. The abundance and optical properties of these crystals effectively scatter sunlight, making the contrail visible shortly behind the aircraft (Schumann et al., 2012).

A contrail's persistence and size highly depend on the ambient humidity, which is directly driven by the meteorological situation (Gierens et al., 1999). Within a dry setting, the ice crystals sublimate quickly, and the contrail vanishes within seconds or minutes after formation. The opposite case is an ice-supersaturated environment. Here the crystals continuously grow, and formations may persist, spread, and sometimes evolve into cirrus-like clouds – contrail cirrus. Within this spectrum of short- to long-lived contrails, the persistent range (several hours) is of particular interest as these formations can influence the Earth's radiative balance by both reflecting incoming sunlight and trapping outgoing longwave radiation (Liou, 1986; Minnis et al., 2004).

Despite large uncertainties arising from the complex microphysical and optical properties of contrail cirrus and their effect on radiative forcing, the net effect has been shown to be warming (Burkhardt & Kärcher, 2011; D. S. Lee et al., 2021). Simulations estimate that the mean global coverage of contrails varies between 0.1 and 2 % depending on the classification of persistence and visibility (Boucher, 1999; Burkhardt & Kärcher, 2011). Regionally, coverage can exceed 10%, particularly within high traffic areas such as the North Atlantic flight corridor (Bock & Burkhardt, 2016; Teoh et al., 2024). Estimates of aviation-induced cirrus radiative forcing have evolved significantly with advances in scientific understanding and modeling capabilities; however, annual mean values still vary considerably - typically ranging from approximations between 20 and 70 mW m^{-2} - reflecting substantial uncertainties (Burkhardt & Kärcher, 2011; D. S. Lee et al., 2021; Teoh et al., 2024).

The presence of these uncertainties complicates the impact of assessments and the evaluation of mitigation potential, thereby highlighting the value of continued scientific research. Nevertheless, contrail avoidance remains a promising and actionable opportunity to reduce aviation's contribution to anthropogenic warming (Teoh et al., 2020; Sausen et al., 2024). Simulations suggest that targeted flight planning strategies—such as selective routing or altitude adjustments—could reduce contrail effective radiative forcing (ERF) by up to 20% without major operational penalties (Teoh et al., 2020), and by as much as 70% if minimal increases in flight time and fuel consumption are accepted (Martin Frias et al., 2024; Teoh et al., 2020). Effective implementation and evaluation of such strategies, including the use of alternative fuels, rely on improved understanding of contrail formation conditions and their radiative impacts to ensure both meaningful climate benefit and operational feasibility (Martin Frias et al., 2024; Sonabend-W et al., 2024).

A recent study by Prather et al., (2025), published in Nature investigated the risk for a non-CO2 reduction measure that comes at the expense of additional CO2 emissions, considering uncertainties. The authors define a new metric, the global warming potential per year of activity and apply it to the uncertainty range for CO2 and non-CO2 emissions provided by Lee et al., 2021. Using these uncertainties, their risk assessment quantifies the probability for a positive climate outcome of a non-CO2 reduction of xx % compared to a 1% increase in CO2, see Figure 2 (Voigt, 2025). This high probability for a positive outcome of contrail avoidance provides a scientific base to further develop the concept for contrail avoidance trials in order to advance their implementation into the international air navigation systems.

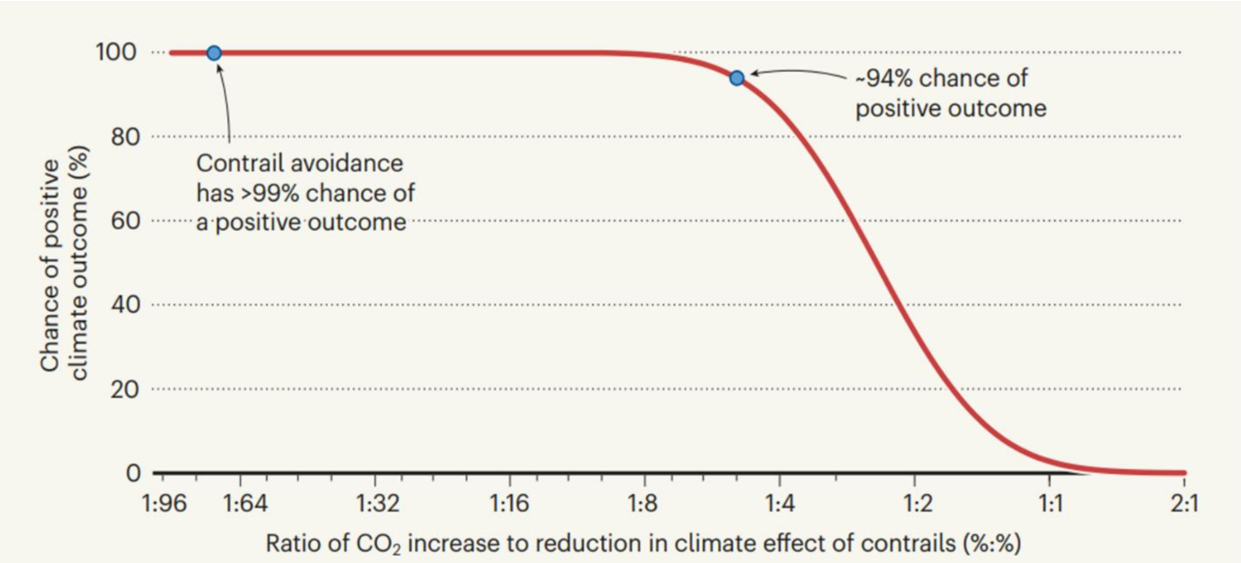

Figure 2: (Voigt, 2025). ***A decision-making tool to guide climate action in the aviation sector.*** *Global warming caused by aircraft results both from carbon dioxide emissions and from non-CO2 effects. Strategies for reducing non-CO2 effects can increase CO2 emissions, making it hard to assess the overall impact on global warming. Prather et al. 2025 have developed 'risk curves' that plot the likelihood of a net positive climate outcome when a 1% increase in CO2 emissions is offset by an N% reduction of a non-CO2 effect. For instance, a strategy that increases CO2 emissions by 1% but lowers contrail-induced warming by 5% (a 1:5 ratio on the x axis) has an approximately 94% chance of mitigating global warming (taking into account the effects of one year of global flights over a 100-year period). To give a specific example, optimization of flight paths could reduce contrail-induced warming by 73% while increasing CO2 emissions by less than 1% (Frias et al.,2024). The risk curve shows that this strategy has a greater than 99% chance of mitigating global warming (Adapted from Fig. 3a of Prather et al., 2025).*

In parallel with growing scientific and operational interest, the regulatory landscape in Europe is evolving to address aviation's non-CO_2 climate effects. As of 2025, a formal monitoring, reporting, and verification (MRV) framework has been introduced under the EU Emission Trading System (ETS) to capture these impacts, mainly these from contrail formation and NO_x emissions. This development signals a shift towards more comprehensive climate accountability in aviation. Looking ahead, the European Commission expected to implement economic measures from 2028 onward, which could involve pricing mechanisms, incentive schemes, or mitigation obligation linked to non-CO_2 effects. These changes increase the urgency for evidence-based strategies that can be operationalized within existing air traffic systems, laying the groundwork for integrating climate-optimized routing into both policy and practice.

This report outlines a conceptual approach for contrail avoidance flights, aiming to identify operational strategies that minimize aviation's non-CO_2 climate impact—particularly the formation of persistent contrails and contrail cirrus. The objectives include improving scientific understanding of contrail formation conditions, evaluating the climate effectiveness of tactical avoidance, and assessing the feasibility of implementation within existing flight planning systems. The planned rerouting trial, compromising approximately 400 real avoidance flights, provides a critical opportunity to examine these objectives under operational conditions. The purpose of this trial is to explore the potential of contrail mitigation through targeted flight adjustments and to define key requirements for future operational integration. This report scopes the underlying scientific context, outlines methodological components, and provides initial guidance for designing contrail avoidance trials.

2. Operational Process

2.1. FLIGHTKEYS's Operational Overview

The trials will be conducted using the latest version of the software (ng-Visual 5D) used by TUIFly at the time of initiating contrail avoidance flights, within their TUIFly production environment, which includes an enhanced contrail cost feature.

FLIGHTKEYS has integrated contrail prediction areas based on the Contrail Cirrus Prediction Model (CoCiP) as cost-dependent restrictions. NetCDF files containing contrail radiative forcing values are retrieved from the Contrails API every six hours – as per internal policy, covering all flight levels. These files are then transformed into GRIB-format weather layers. Each grid cell contains a warming potential value expressed in joules per meter (J/m).

When a flight traverses a cell, the distance travelled (in meters) is multiplied by the warming potential (J/m) to estimate the total energy forcing in joules (J) for that segment (as specified in Figure 3 and Equation 1). This energy forcing (EF) is then converted into an equivalent CO_2 warming impact over 100 years (CO_2e,100), which is assigned a monetary value. The monetary value is allocated based on a discussion with the airlines and their contrail avoidance needs. The higher the value the more strict the avoidance and vice versa. Airlines are welcome to change and it is often assigned based on calculations made from airline policies or could be calculated with reference to carbon cost accounting. The optimizer incorporates this contrail cost into the total cost function, aiming to optimize cost minimization.

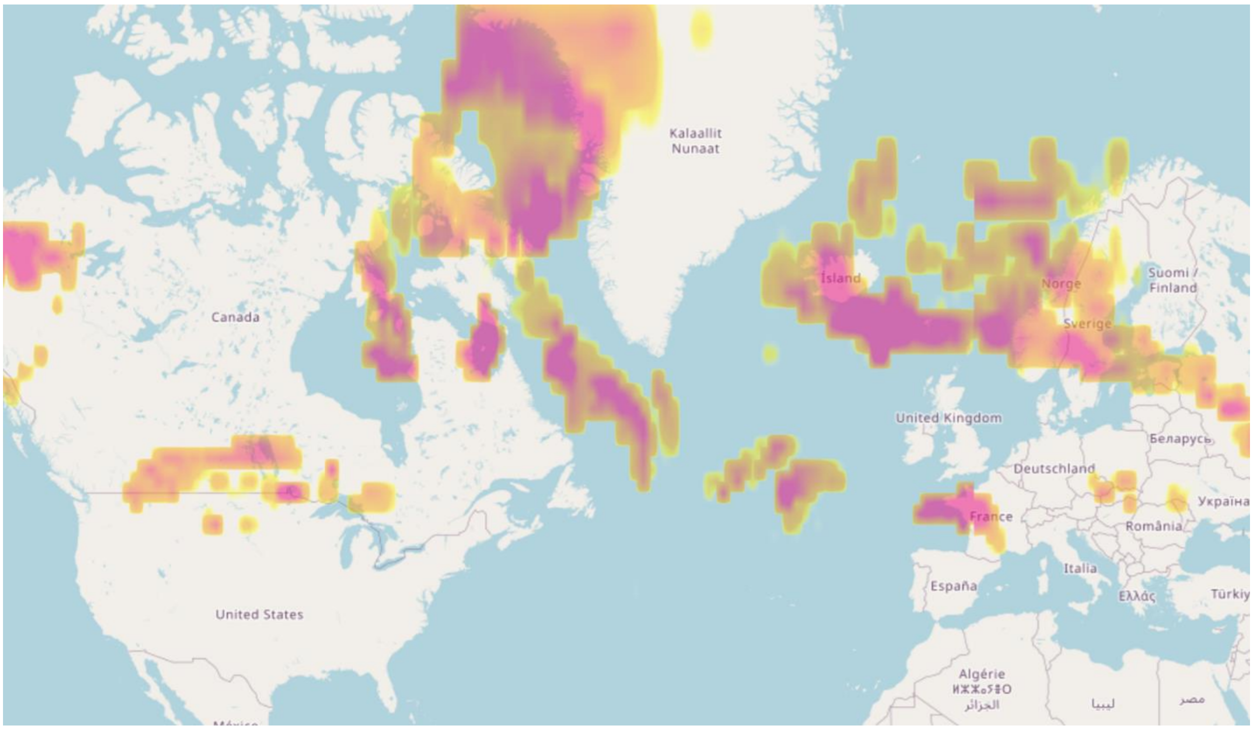

Figure 3: Screenshot of contrail prediction areas as seen in ng-Visual 5D map view at flight level 350

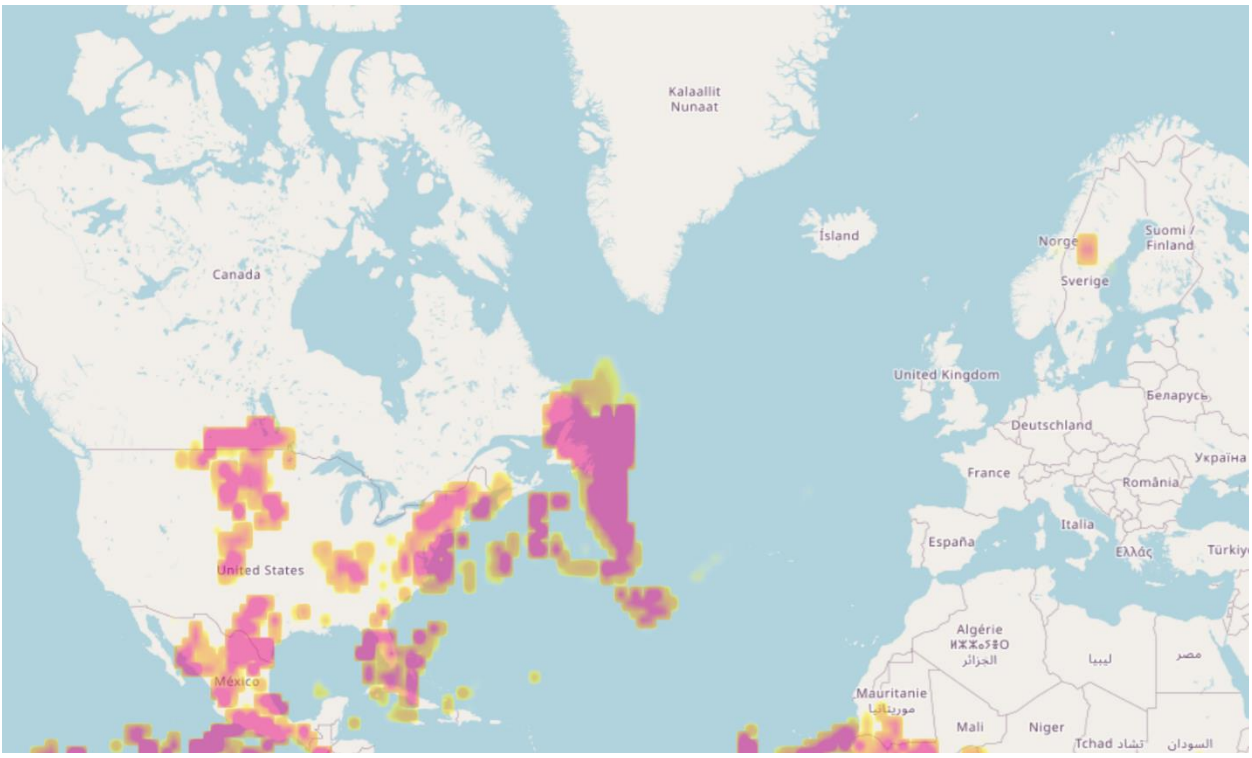

Figure 4: Screenshot of contrail prediction areas as seen in ng-Visual 5D map view at flight level 400

The map view in Figure 2, above, indicates the contrails that can be found at a specific altitude. This is only a two-dimensional representation of contrails at a given moment at a specific altitude. At flight level 400 contrails change and are rather seen as depicted in the map view in Figure 2.2, above.

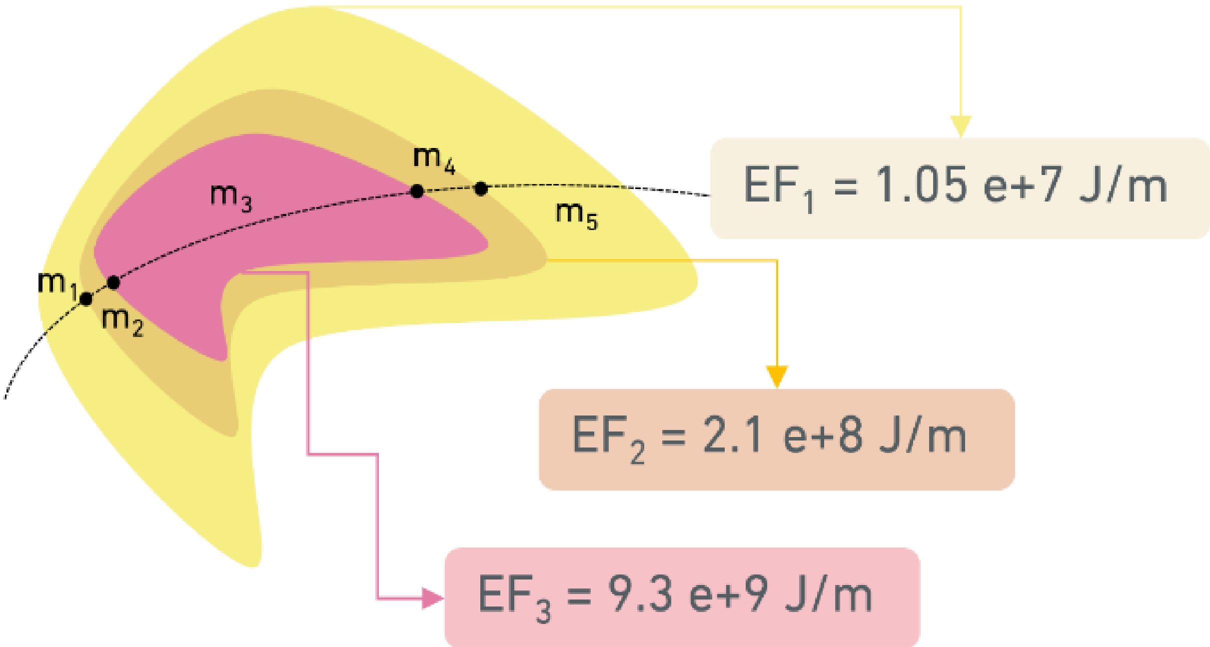

Figure 5: Example of various numerical calculations used to represent warming potential in ng-Visual 5D

$$\text{EFtotal [J]} = \text{EF1} \cdot (\text{m1} + \text{m5}) + \text{EF2} \cdot (\text{m2} + \text{m4}) + \text{EF1} \cdot \text{m3}$$

Flights are evaluated for contrail avoidance approximately six hours* before departure. If a flight is predicted to form a warming contrail, it is highlighted in the dispatcher desk for potential re-optimization. Flights are categorized according to their estimated warming potential (very high, high, medium, or low) to facilitate prioritization.

**Version details, price assigned for optimization, grid resolution, and evaluation trigger are still subject to final definition.*

2.2. TUIFly's Operational Overview

The decision-making process begins by evaluating a list of avoidance flights, as identified by the Flight Planning System and depending on the prevailing weather conditions. If avoidance trajectories are recommended and avoidance routes meet the excess time and fuel thresholds, the dispatch will release the contrail avoidance optimized flight plan. Currently, these thresholds have been set at a maximum of 2% extra fuel burn and time of flight, but they will be reassessed and tested within the upcoming trials. The first preference is vertical avoidance, assessed based on weather, climb/descent segments, flight level limits, and profile consistency (avoidance of excessive climbs and descents). If vertical avoidance is found unviable, lateral avoidance or a combination of both may also be considered. If the excess fuel burn and time of flight are acceptable, an avoidance flight plan is filed; otherwise, the regular plan is filed and listed as an observation flight and flight crew is informed accordingly.

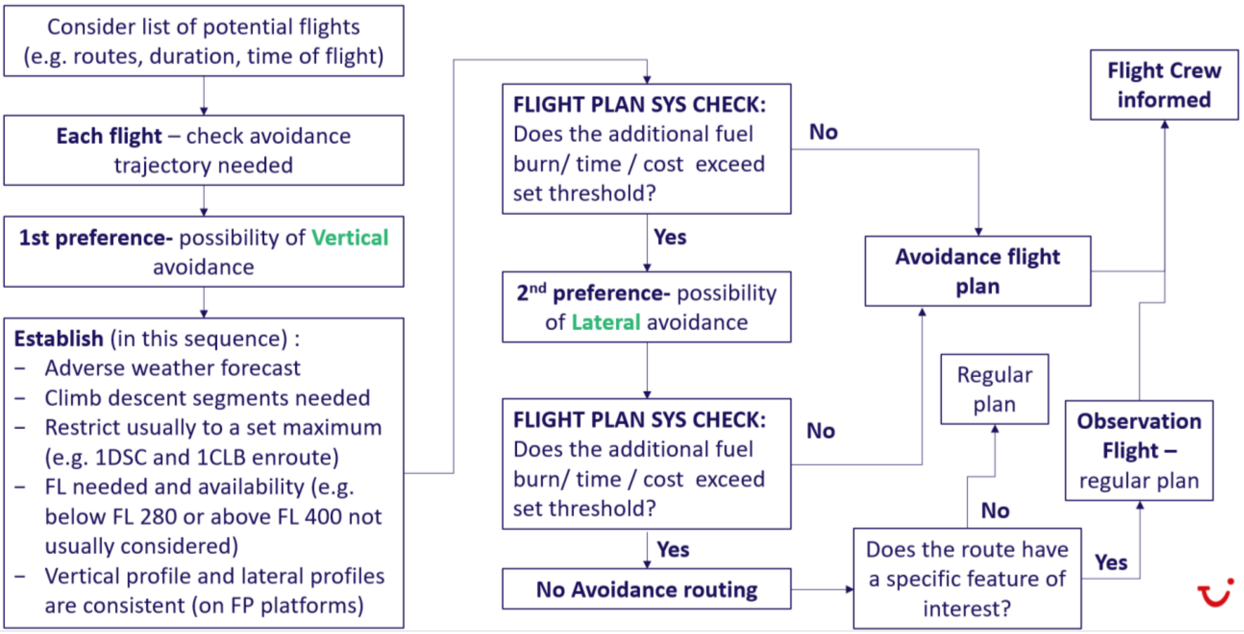

Figure 6: Conceptual flowchart for TUIFly's rerouting decision making.

3. Conceptual Framework for Contrail Avoidance Flights

3.1. Current Strategies for Contrail Mitigation

Efforts to reduce the climate impact of aviation-induced contrails have evolved considerably over the past two decades, driven by an increasing understanding of their radiative forcing potential. Strategies for contrail mitigation can be broadly categorized into three domains: technological, operational, and policy driven approaches:

- Technological measures include the development of alternative fuels (e.g., sustainable aviation fuels, SAFs) with lower aromatic and soot content, as well as hydro processed fuels, which offer improved combustion properties and significantly lower non-volatile particulate emissions. In parallel, future propulsion systems, including hydrogen-based engines ad hybrid electric concepts, are under investigation for their potential to reduce or eliminate CO_2 emissions and modify water vapor and particulate outputs, thereby influencing contrail formation dynamics.
- Operational measures primarily target short–term changes to flight trajectories – for instance, altering altitude or heading to avoid ice-supersaturated regions (ISSRs) conducive to contrail formation.
- Policy and market mechanisms have been proposed to incentivize contrail avoidance, such as incorporating non-CO_2 climate effects into emission trading schemes or developing routing priorities that include climate-optimal paths.

While theoretical and simulated studies have highlighted the substantial potential of operational avoidance. Transitioning from concept to implementation has revealed several critical technical and logistical limitations, these include:

- Forecast Uncertainty: The accuracy of high-altitude humidity forecast remains a major constraint. Contrail formation is highly sensitive to local variations in temperature and relative humidity with respect to ICE (RHi), yet current operational weather models often struggle to resolve these parameters with sufficient spatial and temporal precision.
- Air Traffic Control (ATC) Constraints: In high-density airspace, rerouting flights vertically or laterally can pose challenges for maintaining separation minima and overall traffic flow. The capacity of ATC systems and procedural limitations (e.g., fixed route structures) must be considered in real-time implementations. These constraints directly impact the ability to deliver the required capacity, particularly in busy or congested sectors.
- Evaluation and Verification: The sporadic and dynamic nature of contrail formation, along with limited availability of high-resolution satellite data or consistent observational coverage, complicates post-flight assessment of avoidance effectiveness.

These limitations have motivated a range of recent trials and simulations aimed at better quantifying both the potential benefits and the operational trade-offs of contrail avoidance:

- Teoh et al. (2020) performed a simulation study consisting of six weeks of air traffic over Japanese airspace, applying a trajectory optimization algorithm focused on high-impact flights. The analysis revealed that just 2.2% of flights were responsible for 80% of potential contrail climate impact. Optimized routing of these flights resulted in a 59% reduction in contrail impact with marginal fuel penalty of only 0.014%.

- Sausen et al. (2024) conducted the first large-scale contrail avoidance trial over northeastern Europe. Involving 2690 contrail avoidance flights and 3398 observation flights. Using MSG/SEVIRI satellite data for evaluation, the study found a significantly higher probability of contrail formation in the control group, indicating that targeted rerouting can indeed reduce contrail occurrences when avoidance measures are taken.
- Sonabend et al. (2024) trialed real-time contrail avoidance in operational conditions, involving 44 commercial flights (22 avoidance, 22 control). The avoidance group exhibited a 64% decrease in contrail detection, as confirmed by observational data, with an associated 2 % increase in fuel burn, highlighting the trade-off space between climate benefit and operational costs.
- Frias et al. (2024) analyzed over 85000 commercial flights using an operational flight planning system integrated with contrail prediction (CoCiP). The study demonstrated a 73% reduction in contrail climate forcing through optimized routing, with only 0.11% increase in fuel burn and minimal cost impact. Two integration methods were tested: a cost-based approach and a polygon-based approach. The results demonstrate the practical feasibility of implementing large-scale contrail avoidance within existing airlines.

In addition to findings in academic literature, earlier work by the trial partners – including smaller trials, simulations studies, and internal strategic discussions – has revealed key insights into the technical and operational challenges of contrail mitigation.

3.1.1. DLR – Insights from Previous Work

The AKKL (*Arbeitskreis klimaneutrale Luftfahrt,* Working Group on Climate-Neutral Aviation) is a German government-led initiative bringing together experts from politics, industry, research, and civil society to develop strategies for making aviation climate-neutral. It focuses on advancing sustainable aviation fuels (SAF), new propulsion technologies, and more efficient flight operations. Within this working group DLR has evaluated a 100-flights trial, where contrail effects of different rerouted flight trajectories could be compared to the initially planned route. During the 100-flights trial, DLR deployed its fully automated software pipeline to evaluate its capability to process, simulate, and analyze flight trajectories and their atmospheric impacts.
DLR is an internationally recognized expert for the analysis and scientific assessment of contrail mitigation, e.g. by sustainable aviation fuels (Dischl et al., 2024; Voigt et al., 2021) modern engine technologies (Märkl et al., 2024) and contrail avoidance (Voigt, 2025), as also documented in the recent ICAO report, 2025.

In addition to providing further insights into the feasibility of targeted avoidance maneuvers, DLR's work also offered valuable perspectives on:

- Unclear rerouting strategies and inconsistent use of prediction models – Variations in how prediction models were applied, combined with a lack of standardized rerouting logic and the influence of human decision-making such as pilot or dispatcher choices, introduced ambiguity in evaluating the effectiveness and comparability of avoidance maneuvers.
- Limited satellite detection capabilities – Natural cloud cover and high traffic density in certain airspaces made it difficult to reliably detect and attribute contrails, reducing the availability and accuracy of observational data.
- Impact of delayed flights on evaluation – Flight delays distort statistical analyses, as the originally planned takeoff times no longer align with the simulated mitigation scenarios, making it difficult to assess whether a rerouting strategy was effective or not.

- Effect of high-impact regions – Flights routed through areas with a high likelihood of contrail formation can disproportionately influence overall success metrics. A single well-executed avoidance maneuver in such a region can significantly improve the perceived success rate for a fleet.

3.1.2. TUIFly – Insights from Previous Work

To date, TUIFly has carried out more than 197 contrail avoidance flights, including 25 flights from the AKKL 100-flight trial and three full-network trials conducted over separate one-week periods. In doing so, it highlights a range of systemic and practical challenges that must be addressed to enable effective contrail mitigation in routine operations:

- Pilot behavior and training remain focused on fuel efficiency, with limited awareness of contrails and their climate impact, reducing the likelihood of voluntary mitigation actions.
- Workers' councils are often cautious about procedural changes and data sharing, which can delay implementation or limit access to essential flight data.
- Aircraft manufacturers restrict the sharing of specific performance data with airlines, making it necessary to rely on generic models—an approach that can introduce significant inaccuracies unless properly calibrated.
- The business case for contrail avoidance is currently weak, as operational adjustments often involve increased fuel consumption, with no direct financial incentive or regulatory support in place.
- Flight planning practices are optimized for cost efficiency in the short term and often lack mechanisms to integrate climate impact. This reinforces the need for calibrated models to assess less impactful routing options through large contrail-prone regions, along with clearer internal policies and decision-making frameworks.
- Contrail regions, as predicted by models, frequently turn out to be larger than expected—up to 1,600 nautical miles in length and spanning altitude bands of up to 7,000 feet—complicating route adjustments.
- While air traffic control (ATC) has generally been supportive, their focus on standard routing can pose challenges for accommodating deviation requests.
- Contrail avoidance is often limited by inadequate atmospheric conditions, high fuel penalties, and altitude or route constraints imposed by ATC.
- So far, observed excess fuel consumption due to rerouting has been low—but the dataset is not yet representative enough to draw broader conclusions and is currently being undertaken under strict threshold constraints (< 2.5 % excess fuel)
- The use of generic aircraft and engine performance models introduces uncertainty and may lead to misleading recommendations if not adapted to specific fleet characteristics.
- The trial setup itself was limited in scope—focused only on pre-selected flights within specific regions and seasons and excluded flights with high excess fuel risks. In addition, ATC was informed in advance on most occasions, which may not reflect standard operations.

3.1.3. FLIGHTKEYS – Insights from Previous Work

Since the beginning of 2025, FLIGHTKEYS has actively participated in two distinct sets of operational trials in collaboration with different airline partners. These trials were designed to evaluate the practical implementation of contrail mitigation strategies within real-world flight operations. The goal was to assess the effectiveness of contrail-avoidance flight planning and to gather operational feedback from dispatchers and flight crews.

Trial 1: Collaboration with American Airlines (AAL)

- The objective of this trial was to target and reduce the formation of high-impact contrails over the North Atlantic region.
- The trial focused on specific transatlantic city pairs and selected aircraft types operated by American Airlines.
- The trial was conducted over a period of several months, allowing for extensive data collection and pattern analysis.
- Contrail-avoidance flight plans were generated using FLIGHTKEYS technology and evaluated for operational feasibility.
- Key Takeaway: This extended trial provided valuable insights into long-haul contrail mitigation and the influence of route selection on environmental impact.

Trial 2: Collaboration with TUIFly

- The objective of this trial was to evaluate contrail mitigation under standard operational conditions ("business as usual") and to better understand day-to-day constraints.
- The trial was conducted over a one-week period, from 17th to 23rd February 2025.
- Flights Considered:
  - A total of 314 flights were assessed.
  - Out of these, 96 flights were filed with contrail-avoidance optimized flight plans.
- Potential Environmental Impact:
  - The potential energy forcing (J) reduction for all 96 flights was estimated with 42.5%—a substantial potential benefit for climate impact mitigation
- Operational Constraints:
- Despite the optimized planning, at least 33 of the 96 flights were unable to fully follow the contrail-avoidance trajectories as planned.

Summary of Findings

- The trials highlighted both the potential climate benefits of contrail-avoidance strategies and the operational challenges involved in their implementation.
- While planning tools like FLIGHTKEYS can generate environmentally optimized flight paths, real-world constraints—particularly airspace management—play a critical role in determining whether these plans can be executed.
- Pilot and dispatcher feedback was essential in identifying current limitations and will inform future developments in both technical solutions and regulatory cooperation.

3.2. Informing Trial Design through Past Lessons Learned

Past contrail mitigation trials have yielded critical insights that inform the structure and priorities of our own trial. Key takeaways include:

- Targeting high-impact flights: As shown in Teoh et al. 2024, and supported by DLR's trial, prioritizing or thresholding for flights with high contrail-forming potential (under possible consideration of contrail properties and persistence) enables a more effective use of mitigation resources and justifies higher fuel penalties where the climate impact may be significant.
- Robust evaluation framework: Findings from Sausen et al. and DLR underscore the need for integrated evaluation pipelines that combine model-based forecasts with satellite evaluation – acknowledging the current limitations in cloud detection and for improved observational data quality.

- Operational realism and coordination: Experience from Sonabend, et al., and FLIGHTKEYS highlights the importance of aligning rerouting strategies with ATC constraints, particularly in congested airspace, and accounting for day-of-flight variables such as delays or route clearances.
- Scalable dispatch integration: Experiences from Martin-Frais, et al., and FLIGHTKEYS trials demonstrate that embedding contrail prediction logic into real-time flight planning is both feasible and essential for large-scale implementation. This trial integrates these insights by further exploring the utility of optimization tools and avoidance strategies within an operational environment.
- Pilot and crew engagement: As identified within TUIFly's evaluation, successful implementation requires increased awareness among flight crews and alignment with existing priorities, such as fuel efficiency. The trial must consider behavioral factors and training needs.
- Data accessibility and calibration: The delimited availability of detailed aircraft performance data highlights the need for using well-calibrated generic models.
- Fuel and cost trade-offs: While DLR and FLIGHTKEYS trials report low observed excess fuel consumptions, the trial design should still anticipate variability and incorporate flexible thresholds for fuel penalties, to balance environmental benefits against economic costs.
- Geographical and seasonal constraints: Trial designs must be mindful of scope limitations observed in previous efforts, ensuring sufficient diversity in routes, season, and weather conditions to build a representative dataset.
- Uncertainty in prediction models: Both DLR and TUIFly noted the undermined effectiveness of rerouting by inconsistent use or interpretation of prediction models. This design emphasizes the idea of standardized, well-documented model outputs and routing decisions.
- Prather et al., 2025 and Voigt, 2025 have shown that the chances for contrail avoidance measures with a positive effect for climate are high, despite many constraints. For a 1% CO2 increase, a contrail climate effect reduction by 5% already has more than 90% of success probability.

These lessons collectively guide a pragmatic yet ambitious approach to trial design—one that balances scientific rigor with operational feasibility and aims to generate transferable insights for routine contrail mitigation.

4. Trial Set Up

Building upon decades of research into contrail formation and mitigation, the current flights trials represent a crucial step towards operationalizing strategies for reducing aviation's climate impact. While previous studies have shown that targeted flight adjustments can significantly reduce the formation of warming contrail, several critical barriers remain. The most critical among these are the limited accuracy of humidity forecasts at cruising altitudes, the dynamic constraints of air traffic management, and the need for standardized, robust evaluation protocols that work in real-world-flight operations.

To address these challenges in a controlled yet operationally relevant setting, the current trial adopts a flight batch allocation strategy for the 400 flights being planned. This approach structures the total proposed set (400 flights), into four targeted batches, each designed to explore solutions for specific scientific questions and operational scenarios. These batches allow for a systematic investigation of contrail prediction reliability, the effectiveness of avoidance maneuvers, the role of seasonal and diurnal variability, and the practical feasibility of implementation under differing airspace conditions.

By aligning each batch with a clearly defined research objective – such as relevant model performance, exploring cost-benefit trade-offs in high density airspace, or testing system responsiveness to short notice favorable re-routing conditions – the trial maximizes learning across a range of relevant operational context. This structured approach not only supports detailed analysis of individual flight outcomes but also helps to identify generalized insights for future large-scale implementation of contrail mitigation strategies.

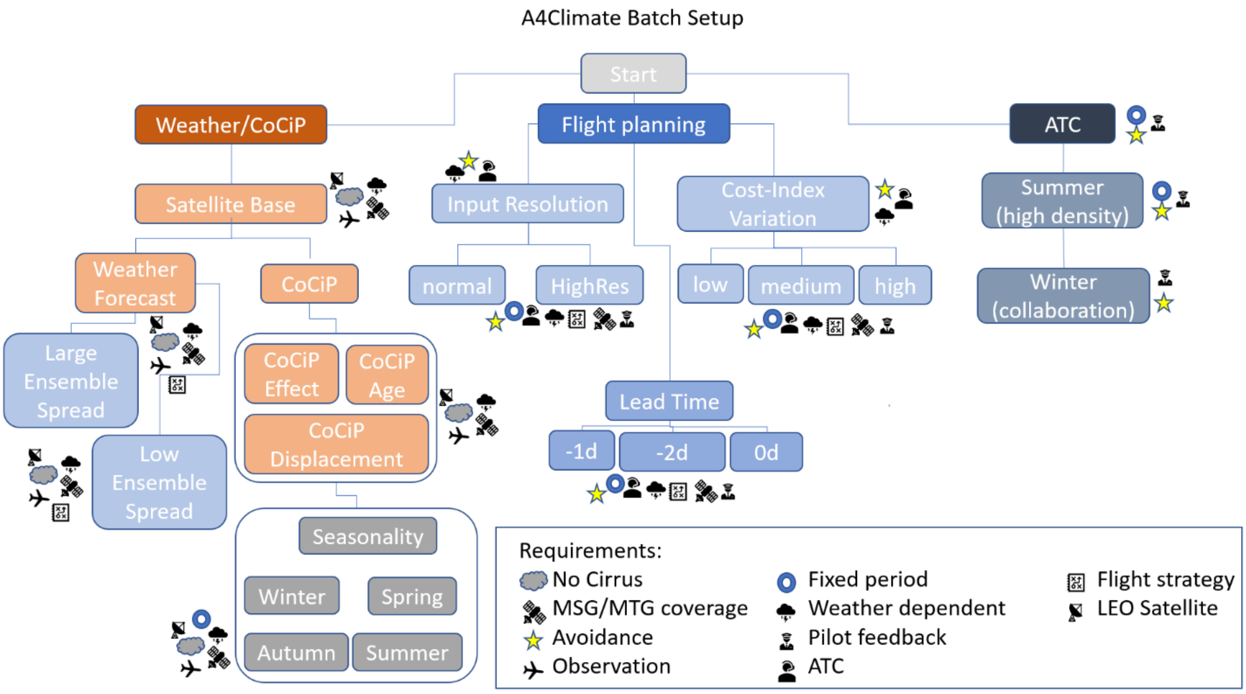

Figure 7: Key Criteria for Identifying and Categorizing Batches.

4.1. Batch 1 – Evaluation of Satellite Capabilities and CoCiP Model Performance

This batch targets the suitable flights for the assessment of satellite-based detection of contrails, with a focus on verifying and evaluating the accuracy of the CoCiP model in predicting contrail formation and evolution. Special emphasis is placed on:

- Lateral spread and age of predicted versus observed contrails.
- Temporal variation on contrail radiative impact by targeting flights across different times of the day (morning, midday, and evening)

The goal is to improve and assess the model's fidelity and understand the daily cycle of contrail climate effects.

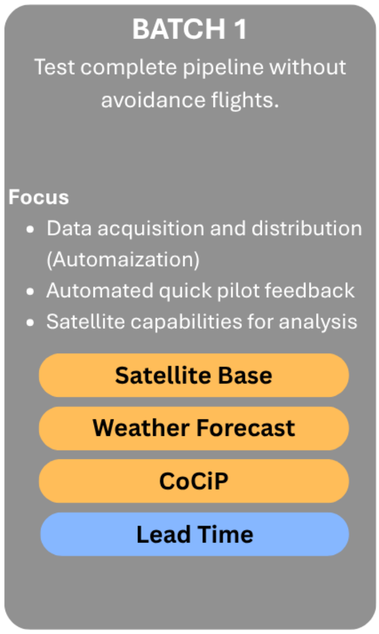

Figure 8: Batch 1 overview

Funded by the European Union

The project has received funding from the European Union`s Horizon Europe research and innovation programme under the Grant Agreement no. 101192301.

4.2. Batch 2 – High-Density Airspace and Air Traffic Control Considerations

Flights in this batch will be undertaken when the traffic density is expected to be high (i.e., the summer season) in certain parts of the airspace. In such a scenario, the operational feasibility of executing a contrail avoidance as planned poses a significant challenge. Tests will be run over the course of a full week to address and assess:

- Investigation of seasonal variability in contrail formation and associated radiative effects.
- Analysis of meteorological conditions specific to summer operations, including the role of weather forecast uncertainty in avoidance planning.
- Practicality of re-routings in congested airspaces, including addressing the likelihood that avoidance plans can be flown as filed under real-world ATC constraints.
- Cost-benefit trade-offs under different contrail scenarios – examining under what conditions (e.g., magnitude of contrail radiative forcing) contrail avoidance is justifiable considering fuel penalties or increased ATC complexity.
- Application of hypothetical CO_2e-based contrail taxation levels to assess their influence on the selection and justification of proposed trajectories.
- Impact of summer weather forecast uncertainties on the planning and effectiveness of avoidance strategies.
- Influence of delays and their implications on the viability and overall benefit of contrail mitigation.
- Evaluation of additional operational and environmental factors that may influence the effectiveness of contrail mitigation strategies.

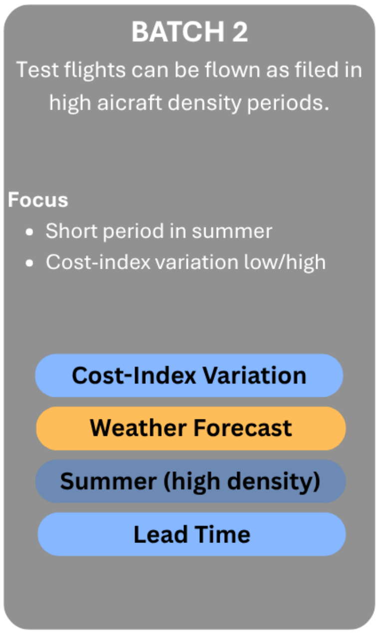

Figure 9: Batch 2 overview

This batch provides critical input for developing dynamic decision thresholds for rerouting in operational contexts.

4.3. Batch 3 – Seasonal and Low-Density Operational Contexts

This batch will take place during winter and will consider scenarios wherein traffic congestion in airspaces is expected to be limited. This will offer unique opportunities to explore contrail mitigation strategies under reduced operational constraints. The tests will be aimed to mirror those of Batch 2 but focus on network-wide impacts in winter. This batch addresses:

- Investigation of seasonal variability in contrail formation and associated radiative effects.
- Analysis of meteorological conditions specific to winter operations, including the role of weather forecast uncertainty in avoidance planning.
- Assessment of whether avoidance plans can be flown as filed, and identification of key ATC constraints that may still influence adherence in lower-density airspace.
- Exploration of rerouting opportunities where ATC constraints are reduced compared to summer conditions.
- Application of hypothetical CO_2e-based contrail taxation levels to analyze their influence on trajectory planning and justification.
- Evaluation of how delays may impact the feasibility and effectiveness of contrail avoidance strategies.
- Analysis of additional factors that may influence the overall effectiveness of mitigation strategies in winter conditions.

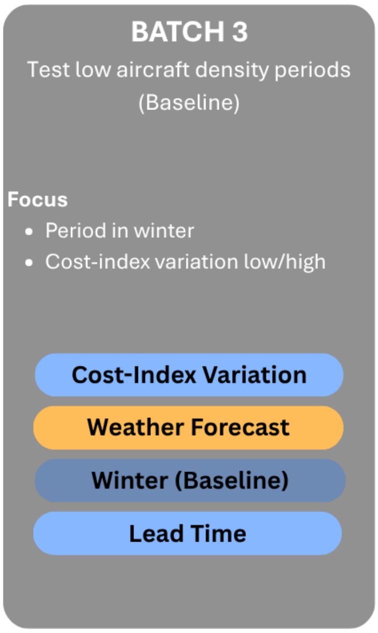

Figure 10: Batch 3 overview

This batch provides critical input for developing dynamic decision thresholds for rerouting in operational contexts.

4.4. Batch 4 – Rapid Response and Opportunistic Avoidance Scenarios

Designed as a buffer batch, this group of flights is intended for real-time execution when conditions for contrail avoidance are especially favorable. It allows to:

- Test the operational responsiveness of the trial setup.
- Validate how quickly avoidance flights can be identified, prepared and implemented under optimal conditions.
- Ensure that "Big Hits" (upper extreme scenarios with strong radiative effects) are included in this trial.

This batch serves as a proving ground for the system's agility and supports learning for future real-time implementation of contrail mitigation strategies.

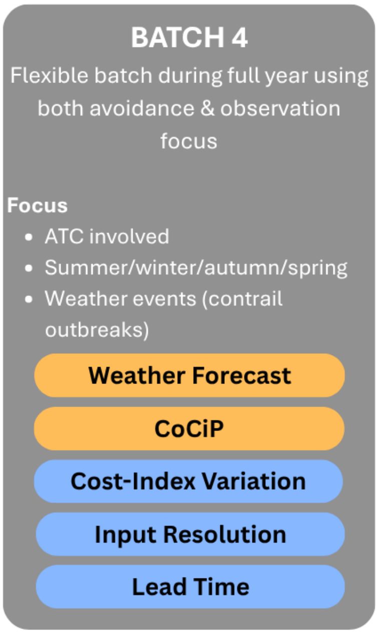

Figure 11: Batch 4 overview

5. Challenges and Horizons

Despite growing evidence supporting the effectiveness of contrail avoidance strategies, the path towards large-scale implementation is shaped by a complex set of operational, regulatory, and technical challenges. The current trial set-up has highlighted a number of these constraints, both in terms of what is achievable under current strategies and where further structural or policy-driven change is needed.

5.1. Operational Constraints

A number of limitations arise from the operational realities of daily airline and air traffic control (ATC) practices. While individual avoidance maneuvers (altitude and heading adjustments) are feasible on a case-by-case basis, their systematic application across a full network remains difficult. Challenges include:

- Air Traffic Management Capacity: In high-density airspace, available maneuvering room is limited. Vertical and horizontal deviations often conflict with sector capacity constraints, particularly during peak hours.
- Summer seasons often place a strain across ANSPs, due to the increased traffic, resulting in a higher chance of rejection of flights plans and less possibilities to fly as filed
- Airline Flight Planning and Dispatch: integrating contrail avoidance objectives into daily flight planning requires new tools, decision support systems, and update procedures – all of which must balance commercial, operational, and environmental trade-offs.
- Forecast Reliability and Timing: the effectiveness of avoidance depends heavily on accurate, timely meteorological forecasts, especially concerning upper tropospheric humidity and ice supersaturation, parameters with known uncertainties.
- Evaluation and Feedback Loops: The absence of near-real-time evaluation methods (e.g., satellite imagery lag or difficulty in interpreting contrail extent) complicates operational learning and model refinement.

5.2. Policy and Institutional Support

For contrail avoidance to scale beyond trial environments, robust policy frameworks and institutional buy-in will be essential. Current routing rules, performance metrics, and environmental regulations are not yet designed to incentivize or even accommodate climate-optimized trajectories. Enabling structural changes might require:

- Clear Regulatory Guidelines: Defining when and how contrail avoidance should be prioritized, including criteria for “high impact” flights and acceptable trade-offs in fuel costs.
- Cross-sectoral Alignment: Aligning goals between air navigation service providers (ANSPs), airlines, and environmental agencies to embed climate impact mitigation as an operational objective.
- Data and Model Standardization: Agreeing on harmonized contrail prediction model, and evaluation metrics across national and regional stakeholders to enable consistent and credible implementation.

Insights from real-world trials will be critical for shaping future EU policy. Trials that link prediction, avoidance, and observation, especially those improving models like CoCiP, can directly inform regulatory design. Findings on feasibility and data accuracy will further support fair and practical integration of non- CO_2 impacts into instruments such as EU ETS.

5.3. Future Collaboration Opportunities

This trial aims to demonstrate the value of strong collaboration between research institutions, airlines, Flight Planning System providers, and ANSPs. Moving forward, deeper integration of operational and research agendas could unlock further potential, including:

- Integration of Contrail Avoidance into ATC Flow Tools: Collaboratively developing ATC decision support systems that incorporate climate impact predictions without compromising the prioritized safety or efficiency.
- Training and Awareness: Embedding contrail awareness into ATC and pilot training to promote shared understanding of the climate implications of rerouting choices.
- Multi-Region Coordination: Creating mechanisms for coordination across flight information regions, especially on transboundary or transatlantic flights, to allow consistent application of avoidance strategies.
- Another contrail avoidance trial approach could be linked to flights across the Atlantic to align ASNPs and airlines from Europe and America.
- Contributing to Other Work Packages: The findings and outcomes of this Work Package will also support and inform related activities within the A4Cliamte project, particularly those under WP4, fostering alignments and knowledge transfer across work streams.
- International context: while EU SESAR projects like *CICONIA* and *CONCERTO* mainly address the important topic of demonstration trials by other airlines with a low number of flights as well as comparing forecast tools or assessing airspace capacity, A4CLIMATE undertakes a first trial with 400 flights to improve operational contrail avoidance tools in a real flight scenario.
- ICAO: Several ICAO ATM topics also target contrail avoidance. The results from this 400 flights trail will be reported to ICAO as well as to stakeholders in the A4CLIMATE stakeholder workshops.

6. Conclusion

As aviation continues to face increasing scrutiny over its environmental footprint, contrail avoidance or the mitigation of contrail formation shows to be one of the most promising near-term strategies to lower climate warming impacts (Prather et al., 2025; Voigt, 2025). Building on over two decades of research, the conceptual design and planned implementation of this flight rerouting trial directly responds to known and projected challenges in this field. These include the operational feasibility of contrail mitigation, the persistent limitations of upper-atmosphere humidity forecasting, and the need for robust, real-world validation of predictive models and their associated climate benefits.

This trial is uniquely structured to address open questions through a systematic batching approach. By aligning each batch with specific scientific and operational objectives – such as validating the accuracy of the CoCiP model, quantifying trade-offs in high-density airspace, and exploring seasonal and diurnal variability – this study opens possibilities for further insights into the practical implementation of contrail avoidance strategies. These efforts build upon and extend prior trials and simulation studies, while integrating the latest research from scientific institutions and the operational expertise of aviation industry partners.

Importantly, this trial does not exist in isolation. It is part of a broader ecosystem of technological, operational, and policy-driven efforts aimed at reducing aviation's climate impact. While alternative fuels and next-generation propulsion systems represent vital long-term decarbonization strategies, their widespread deployment will take time. In contrast, contrail avoidance stands out as the most immediately actionable approach, offering the potential for rapid implementation and near-term climate benefits. When targeted effectively, particularly at the relatively small fraction of flights responsible for the majority of contrail-induced warming, contrail avoidance can deliver measurable reductions in non-CO_2 climate forcing with minimal operational disruption.

To fully realize this potential, however, further progress is essential. Forecast uncertainty, ATC constraint, and the lack of standardized evaluation protocols remain significant hurdles. Addressing these will require deeper integration of contrail-aware decision-making into flight planning systems and ATC flow management tools, as well as enhanced observational capabilities of post-flight assessments.

Moreover, the success of mitigation efforts as an operational strategy will depend on strong policy support and institutional alignment. Clear regulatory frameworks that acknowledge and incentivize climate-optimized rerouting are essential to move isolated trials to widespread adoption. Equally important is the cross-sectional collaboration among airlines, air traffic management, scientific community and regulatory bodies to ensure consistent implementation. Building operational readiness through targeted training and raising awareness among pilots, dispatchers, and air traffic controllers will be crucial steps toward embedding contrail avoidance into standard aviation practices.

In conclusion, this trial represents more than a scientific investigation – it serves as a testbed for future-ready aviation. By combining predictive modeling, operational experimentation, and strategic collaboration, it lays the groundwork for the widespread adoption of climate-conscious routing. The trial aims to clarify success rates and practical boundaries of contrail avoidance, laying the foundation for assessing its scalability in wider aviation contexts.

Bibliography

Appleman, H. (1953). *The Formation of Exhaust Condensation Trails by Jet Aircraft*. https://doi.org/10.1175/1520-0477-34.1.14

Bock, L., & Burkhardt, U. (2016). Reassessing properties and radiative forcing of contrail cirrus using a climate model. *Journal of Geophysical Research: Atmospheres*, *121*(16), 9717–9736. https://doi.org/10.1002/2016JD025112

Boucher, O. (1999). Air traffic may increase cirrus cloudiness. *Nature*, *397*(6714), 30–31. https://doi.org/10.1038/16169

Burkhardt, U., & Kärcher, B. (2011). Global radiative forcing from contrail cirrus. *Nature Climate Change*, *1*, 54–58. https://doi.org/10.1038/NCLIMATE1068

CICONIA. (2025, July 30). CORDIS | European Commission | Climate Effects Reduced by Innovative Concept of Operations - Needs and Impacts Assessment. https://cordis.europa.eu/project/id/101114613

CONCERTO. (2025, July 30). CORDIS | European Commission | dynamicC cOllaboration to geNeralize eCo-friEndly tRajecTOries. https://cordis.europa.eu/project/id/101114785

Dischl, R., Sauer, D., Voigt, C., Harlaß, T., Sakellariou, F., Märkl, R., Schumann, U., Scheibe, M., Kaufmann, S., Roiger, A., Dörnbrack, A., Renard, C., Gauthier, M., Swann, P., Madden, P., Luff, D., Johnson, M., Ahrens, D., Sallinen, R., … Le Clercq, P. (2024). Measurements of particle emissions of an A350-941 burning 100% sustainable aviation fuels in cruise. *Atmospheric Chemistry and Physics*, *24*(19), 11255–11273. https://doi.org/10.5194/acp-24-11255-2024

Fit for 55 and ReFuelEU Aviation | EASA. (2025). https://www.easa.europa.eu/en/light/topics/fit-55-and-refueleu-aviation

Gierens, K., Schumann, U., Helten, M., Smit, H., & Marenco, A. (1999). A Distribution Law for Relative Humidity in the Upper Troposphere and Lower Stratosphere Derived from Three Years of MOZAIC Measurements. *Annales Geophysicae*, *17*, 1218–1226.

Hoose, C., & Möhler, O. (2012). Heterogeneous ice nucleation on atmospheric aerosols: A review of results from laboratory experiments. *Atmospheric Chemistry and Physics*, *12*(20), 9817–9854. https://doi.org/10.5194/acp-12-9817-2012

ICAO. (2025). *ICAO Environmental Report 2025*. The International Civil Aviation Organization. https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2025/ICAO%20EnvReport%202025.pdf

IEA (The International Energy Agency). (2025). *Net Zero by 2050*. https://www.iea.org/reports/net-zero-by-2050

Kärcher, B. (2018). Formation and radiative forcing of contrail cirrus. *Nature Communications*, *9*(1), 1824. https://doi.org/10.1038/s41467-018-04068-0

Kärcher, B., Burkhardt, U., Bier, A., Bock, L., & Ford, I. J. (2015). The microphysical pathway to contrail formation. *Journal of Geophysical Research: Atmospheres*, *120*(15), 7893–7927. https://doi.org/10.1002/2015JD023491

Klöwer, M., Allen, M. R., Lee, D. S., Proud, S. R., Gallagher, L., & Skowron, A. (2021). Quantifying aviation's contribution to global warming. *Environmental Research Letters*, *16*(10), 104027. https://doi.org/10.1088/1748-9326/ac286e

Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C. N., Lim, L. L., Owen, B., & Sausen, R. (2009). Aviation and global climate change in the 21st century. *Atmospheric Environment*, *43*(22), 3520–3537. https://doi.org/10.1016/j.atmosenv.2009.04.024

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., Gettelman, A., De León, R. R., Lim, L. L., Lund, M. T., Millar, R. J., Owen, B., Penner, J. E., Pitari, G., Prather, M. J., … Wilcox, L. J. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., Trisos, C., Romero, J., Aldunce, P., Barret, K., Blanco, G., Cheung, W. W. L., Connors, S. L., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., … Park, Y. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland*. Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647.001

Lee, J. J., Lukachko, S. P., Waitz, I. A., & Schafer, A. (2001). HISTORICAL AND FUTURE TRENDS IN AIRCRAFT PERFORMANCE, COST, AND EMISSIONS. *Annual Review of Environment and Resources*, *26*(Volume 26, 2001), 167–200. https://doi.org/10.1146/annurev.energy.26.1.167

Leipold, A., Aptsiauri, G., Ayazkhani, A., Bauder, U., Becker, R.-G., Berghof, R., Claßen, A., Dadashi, A., Dahlmann, K., Dzikus, N., Flüthmann, N., Grewe, V., Göhlich, L., Grimme, W., Günther, Y., Jaksche, R., Jung, M., Knabe, F., Kutne, P., … Zill, T. (2021). *DEPA 2050 – Development Pathways for Aviation up to 2050 (Final Report)*. https://elib.dlr.de/142185/

Liou, K.-N. (1986). *Influence of Cirrus Clouds on Weather and Climate Processes: A Global Perspective*. https://journals.ametsoc.org/view/journals/mwre/114/6/1520-0493_1986_114_1167_ioccow_2_0_co_2.xml

Märkl, R. S., Voigt, C., Sauer, D., Dischl, R. K., Kaufmann, S., Harlaß, T., Hahn, V., Roiger, A., Weiß-Rehm, C., Burkhardt, U., Schumann, U., Marsing, A., Scheibe, M., Dörnbrack, A., Renard, C., Gauthier, M., Swann, P., Madden, P., Luff, D., … Le Clercq, P. (2024). Powering aircraft with 100% sustainable aviation fuel reduces ice crystals in contrails. *Atmospheric Chemistry and Physics*, *24*(6), 3813–3837. https://doi.org/10.5194/acp-24-3813-2024

Funded by the European Union

The project has received funding from the European Union`s Horizon Europe research and innovation programme under the Grant Agreement no. 101192301.

Martin Frias, A., Shapiro, M. L., Engberg, Z., Zopp, R., Soler, M., & Stettler, M. E. J. (2024). Feasibility of contrail avoidance in a commercial flight planning system: An operational analysis. *Environmental Research: Infrastructure and Sustainability*, *4*(1), 015013. https://doi.org/10.1088/2634-4505/ad310c

Minnis, P., Ayers, J. K., Palikonda, R., & Phan, D. (2004). Contrails, Cirrus Trends, and Climate. *Journal of Climate*, *17*(8), 1671–1685. https://doi.org/10.1175/1520-0442(2004)017<1671:CCTAC>2.0.CO;2

Prather, M. J., Gettelman, A., & Penner, J. E. (2025). Trade-offs in aviation impacts on climate favour non-CO2 mitigation. *Nature*, 1–6. https://doi.org/10.1038/s41586-025-09198-2

Sausen, R., Hofer, S., Gierens, K., Bugliaro, L., Ehrmanntraut, R., Sitova, I., Walczak, K., Burridge-Diesing, A., Bowman, M., & Miller, N. (2024). Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world? *Meteorologische Zeitschrift*, *33*(1), 83–98. https://doi.org/10.1127/metz/2023/1157

Sausen, R., Isaksen, I., Grewe, V., Hauglustaine, D., Lee, D. S., Myhre, G., Köhler, M. O., Pitari, G., Schumann, U., Stordal, F., & Zerefos, C. (2005). Aviation radiative forcing in 2000: An update on IPCC (1999). *Meteorologische Zeitschrift*, 555–561. https://doi.org/10.1127/0941-2948/2005/0049

Schumann, U. (1996). On conditions for contrail formation from aircraft exhausts. *Meteorologische Zeitschrift*, 4–23. https://doi.org/10.1127/metz/5/1996/4

Schumann, U. (2005). Formation, properties and climatic effects of contrails. *Comptes Rendus Physique*, *6*(4), 549–565. https://doi.org/10.1016/j.crhy.2005.05.002

Schumann, U., Graf, K., Mannstein, H., & Mayer, B. (2012). Contrails: Visible Aviation Induced Climate Impact. In U. Schumann (Ed.), *Atmospheric Physics: Background – Methods – Trends* (pp. 239–257). Springer. https://doi.org/10.1007/978-3-642-30183-4_15

Sonabend-W, A., Elkin, C., Dean, T., Dudley, J., Ali, N., Blickstein, J., Brand, E., Broshears, B., Chen, S., Engberg, Z., Galyen, M., Geraedts, S., Goyal, N., Grenham, R., Hager, U., Hecker, D., Jany, M., McCloskey, K., Ng, J., … Platt, J. C. (2024). Feasibility test of per-flight contrail avoidance in commercial aviation. *Communications Engineering*, *3*(1), 1–7. https://doi.org/10.1038/s44172-024-00329-7

Teoh, R., Engberg, Z., Schumann, U., Voigt, C., Shapiro, M., Rohs, S., & Stettler, M. (2024). Global aviation contrail climate effects from 2019 to 2021. *Atmospheric Chemistry and Physics*, *24*, 6071–6093. https://doi.org/10.5194/acp-24-6071-2024

Teoh, R., Schumann, U., Majumdar, A., & Stettler, M. E. J. (2020). Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption. *Environmental Science & Technology*, *54*(5), 2941–2950. https://doi.org/10.1021/acs.est.9b05608

US Government. (2015). *United States Aviation Greenhouse Gas Emissions Reduction Plan*.

Voigt, C. (2025). Solving aviation's climate-action conundrum. *Nature*, *643*(8073), 921–923. https://doi.org/10.1038/d41586-025-02129-1

Voigt, C., Kleine, J., Sauer, D., Moore, R. H., Bräuer, T., Le Clercq, P., Kaufmann, S., Scheibe, M., Jurkat-Witschas, T., Aigner, M., Bauder, U., Boose, Y., Borrmann, S., Crosbie, E., Diskin, G. S., DiGangi, J., Hahn, V., Heckl, C., Huber, F., … Anderson, B. E. (2021). Cleaner burning aviation fuels can reduce contrail cloudiness. *Communications Earth & Environment*, *2*(1), 114. https://doi.org/10.1038/s43247-021-00174-y