Contrail Impact Task Force

An RMI Initiative

# Understanding Contrail Management: Opportunities, Challenges, and Insights

A Comprehensive Overview Report / July 2024

# Authors and Acknowledgments


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RMI

## About RMI

RMI is an independent nonprofit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut climate pollution at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; Abuja, Nigeria; and Beijing.

## Contributing Organizations

## Supporting Organizations


## Acknowledgments

RMI extends its sincere gratitude to the participants of the Contrail Impact Task Force for their collective efforts and valuable contributions in the development of this report, including the Air Transport Action Group (ATAG), Airlines for America (A4A), and the International Air Transport Association (IATA). This publication represents the ongoing radical collaboration and commitment of stakeholders from across the aviation sector to advance understanding of the climate impact of contrails and explore potential solutions. Special thanks go to the contributing authors and organizations for their expertise and invaluable insights. We also extend our appreciation to the funding organizations whose contributions made this important work possible, including philanthropist Chris Kohlhardt, Alaska Airlines, and Virgin Unite. Your collaboration and dedication are vital to advancing our understanding and management of contrail-induced climate effects.


Although many organizations have been involved in the development of this publication, this document does not necessarily reflect the views of all contributing or supporting organizations but represents the findings and perspectives gathered from various stakeholders as part of the Contrail Impact Task Force.

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# Executive Summary

The following report examines the state of the science and the mitigation of contrails — the line-shaped clouds created by aircraft in cold and humid air — including an overview of the current approaches and efforts to better understand and address their significant climate impact. Contrail management, including contrail avoidance by rerouting flights, presents the opportunity for stakeholders across the aviation sector to engage in radical collaboration to reduce non-$CO_2$ climate impacts alongside ongoing aviation decarbonization efforts.

This report was created in collaboration with participants of the RMI-convened Contrail Impact Task Force, which comprises stakeholders across the aviation sector, including industry organizations, airlines, academic institutions, nongovernmental organizations, private companies, and government entities. It provides a comprehensive overview of the current understanding of the climate impact of contrails as well as research and implementation efforts that support the following key points:

- The climate impact of contrails is significant but solvable. Contrail-induced warming is a concentrated problem with targeted, promising solutions.
- While contrail formation is driven by complex and dynamic atmospheric conditions, forecasting models are being developed to predict persistent contrails. To ensure model accuracy, reliable input data is critical and validation efforts must be scaled up. The most significant source of continued uncertainty is a lack of accurate humidity data at cruising altitude.
- Ongoing flight trials are testing the operational implications of contrail avoidance and providing crucial insights for contrail prediction improvements. Continued collaboration on research and participation in large-scale flight trials can increase the collective understanding of the climate impact of contrails and support the improvement of prediction models.
- Measuring the climate impact of contrails is critical to evaluating the full climate impact of aviation.

This report aims to provide a detailed technical overview for decision makers and stakeholders, including researchers, commercial air carrier operators, international aviation industry organizations, civil society, and policymakers. With this collective understanding, it is our hope that these sector actors further support research efforts and work toward potential non-$CO_2$ industry standards and policies for the global aviation system.

Recommendations in the report include:

- Stakeholders must continue to invest in — and policymakers to incentivize — atmospheric science research and improving the collection and measurement of meteorological data to narrow the uncertainty of how much contrails affect climate warming. Investment should prioritize better weather models, advanced humidity sensors on aircraft, and enhanced satellite imaging coverage.

- Continued and deepened collaboration among stakeholders is needed in the form of flight trials, both simulated and in real life, to demonstrate and assess the feasibility of contrail avoidance solutions. Trials are crucial to improve prediction models, obtain operational know-how, gather practical knowledge on integrating contrail management into airline operations, study possible airspace implications, and further develop and automate the contrail management processes within flight planning tools.

- Air traffic management (ATM) needs to be included and prioritized in research, simulations, and trials to prepare for possible future airspace challenges such as capacity constraints and congestion issues and to adapt systems and processes over time. To ensure contrail avoidance becomes a durable mitigation solution, coordinated implementation spearheaded by ATM authorities is likely essential.

## Why contrails?

Condensation trails — or contrails — created by aircraft flying through cold and humid air can significantly warm the climate. Most contrails dissolve within a few minutes, but in certain conditions, they can persist in the atmosphere, spread out, and become artificial cirrus clouds that trap outgoing heat. This represents an additional climate impact alongside aviation's direct emissions.

In recent years, methods and technologies have been developed to predict and avoid some of the warming impacts created by contrails. By analyzing planned flight trajectories and highly contrail-prone areas, there is an opportunity to develop methods to reroute aircraft around the pockets of very cold and humid air that can make contrails persist, thereby avoiding creating warming contrails. This method is called contrail avoidance. In this resource, we use the term "contrail management" as a comprehensive term for addressing the climate impact of contrails and "contrail avoidance" as a term related to operational avoidance.

Flight planning tools have begun to include contrail prediction models, allowing airlines to plan to avoid warming contrails similar to the way they plan to avoid turbulence.

Although contrail avoidance is a relatively simple solution to a very complex problem, it comes with its own set of challenges that need addressing before a full scale-up of this approach is viable.

## Understanding the full climate impact of aviation

The aviation industry, responsible for about 2% of global $CO_2$ emissions, has committed to reaching net-zero $CO_2$ emissions by 2050, aligning with the Paris Climate Agreement. However, the full climate impact of aviation includes both $CO_2$ emissions as well as non-$CO_2$ effects. Contrail-induced warming is likely to be the most significant driver of the non-$CO_2$ impact of aviation.

It is critical that contrail management does not come at the expense of efforts to decarbonize aviation. We should work to bring down both $CO_2$ emissions and non-$CO_2$ effects in parallel.

## The challenges of predicting where persistent contrails will appear

There are several contrail prediction models being used by researchers and operators in flight trials today. These models are essential for forecasting when and how contrails will form behind aircraft, predicting their characteristics, and understanding their overall influence on climate.

Contrail prediction models are used retroactively to analyze whether past flights generated contrails. They are also used in research and experimental operations to predict and avoid creating warming contrails. On the latter use of these tools, accurately predicting whether a contrail will form still involves significant uncertainty due to factors like weather forecast accuracy, atmospheric interactions, and cloud properties.

One of the most widely used models is the contrail cirrus prediction tool (CoCiP). CoCiP was developed by the German Aerospace Center (DLR) and more recently modified by Breakthrough Energy as Pycontrails, an open-source model that can be adopted and integrated into third-party software applications. Other models in use include Algorithmic Climate Change Functions (aCCFs), also developed by DLR, and the Contrail Evolution and Radiation Model (CERM) and the Aircraft Plume, Chemistry, and Microphysics Model (APCEMM) both developed by Massachusetts Institute of Technology (MIT). Google Research has recently developed a machine-learning-based contrail forecasting model that is also gaining usage. Most recently Google Research and Breakthrough Energy have created a new hybrid contrail prediction model by combining their models and focusing on enhancing accuracy of contrail formation and persistence.

## Increasing prediction model accuracy and validating models

Effective contrail prediction models rely on high-quality input data, including flight trajectories, aircraft and engine parameters, fuel characteristics, and weather data. However, the availability and accuracy of these data inputs is a challenge.

A primary challenge for model accuracy is the lack of sufficient humidity data at cruising altitude. Several efforts are underway to develop contrail-specific humidity sensors to equip on aircraft.

To improve the models, their contrail predictions must be assessed: If contrails were predicted to appear, did they, in fact, do so? To answer this question, observation techniques can be applied to validate contrail prediction. Validation is done by ground observation using cameras pointed at the sky, in-flight observations by flight crews reporting persistent contrails from other aircraft, and satellite observations. To improve validation, more ground-based cameras are needed, use of in-flight observation systems can be expanded, and the resolution and coverage of available satellite imagery must be increased.

Ongoing efforts to improve data quality, increase trials, and enhance validations are crucial for enhancing the reliability of contrail prediction models and building industry confidence in the ability to address the climate impact of contrails.

## Increasing certainty of contrails' impact on the climate

Contrails have a significant climate impact, potentially ranging from half to over three times that of $CO_2$ emissions from aviation. However, quantifying the exact impact of contrails on the climate is difficult due to numerous influencing factors such as dynamic atmospheric conditions (changes in humidity, temperature, wind); time of day, seasonal, and regional variations; cloud interactions (contrail cirrus clouds blending with natural cirrus clouds); and the technological and observational limitations (it is difficult to study the climate effect of a contrail over its entire life span from the ground or from space).

Uncertainty will always be present but can be limited by investing in research related to the influencing factors — especially atmospheric research.

Furthermore, given the high degree of uncertainty in assessing the contrail climate impact of individual flights, assessing the climate impact at a sector level can provide a more holistic account.

## Deciding when to avoid contrails

Limiting the uncertainty about the extent of impact on the climate by contrails is important when determining whether to use additional fuel and emit the associated $CO_2$ to fly around cold and humid areas to avoid contrail-induced warming.

Before making a contrail avoidance decision, the climate impact of the additional fuel burn and the potential contrail-induced warming must be compared to ensure that the avoidance leads to net climate benefits. A consistent climate equivalency metric helps facilitate this comparison.

Although using a single metric like global warming potential (GWP) over a 100-year period (GWP100) simplifies comparisons, it can obscure the trade-offs between additional $CO_2$ emissions and contrail-induced warming given the short-lived climate forcing effects of contrails. Therefore, the choice of climate metric to assess contrail impact will influence the choice of mitigation activity.

This paper discusses the pros and cons of the most relevant metrics for measuring the climate impact of contrails: GWP, which is the primary metric used in international contexts, measures the total energy trapped over a time horizon; global temperature potential (GTP) measures the temperature change at a future point due to an emission; and average temperature response (ATR) measures the average temperature change over a time horizon.

To operationalize contrail avoidance decision-making, a decision matrix can guide whether to avoid contrail formation based on the severity of the contrail's energy forcing (EF) and the additional fuel burn required for avoidance. Calculated decision matrices using GWP20 and GWP100 are included in this paper, but additional matrices could be created based on other metrics and time horizons as well.

## Contrail avoidance in real life

In the past three years, a growing number of contrail avoidance trials have been conducted through collaboration among airlines, scientific institutions, ATM, and tech companies.

Some of the world's biggest airlines are involved in real-life trials and research projects designed to improve the understanding of the climate impact of contrails and best operationalize potential contrail management solutions. Flight planning software providers have started integrating contrail avoidance processes into their software suites, which enables a greater degree of automation, aiding both pre-tactical (before the flight plan is filed) and tactical decision-making.

To keep contrail avoidance moving toward operational viability, continued collaboration among stakeholders is essential in research, trials, tech development, and integration into airline systems and procedures.

Studies and trials have shown that only 2%–16% of flight plans need to be adjusted to avoid 54%–80% of contrail-induced warming. Thus, the process flow for airline-led contrail avoidance involves analyzing all flights, then identifying flights that are most in need of adjusting, submitting new flight plans to air traffic control (ATC), adjusting trajectory along the way as needed (external factors may require unanticipated en route changes), and evaluating operations post-flight to verify avoided warming.

## Contrail climate impact monitoring, reporting, and verification

Monitoring, reporting, and verification (MRV) frameworks provide a standardized approach to measuring the climate impact of a given activity or industry. They are key instruments used by the United Nations Framework Convention on Climate Change and the Convention of Parties in monitoring progress of countries toward the Paris Climate Agreement.

*Monitoring* involves continuous data collection and calculations performed by regulated entities to quantify their climate impact. *Reporting* is the submission of emissions inventories to regulators and verifiers. *Verification* is conducted by third parties to ensure compliance and consistency in monitoring and reporting steps.

An effective MRV framework for contrail impact must be flexible to new research advancements, must have monitoring detailed enough to capture mitigation measures, and should provide uncertainty estimates for its reported values. The framework should also support independent validation of mitigation measures, but it need not express contrail impact in $CO_2$ equivalents ($CO_2e$).

The EU is establishing the first MRV system for aviation’s non-$CO_2$ impacts. The European Commission is to adopt a non-$CO_2$ MRV framework, and starting January 1, 2025, aircraft operators must annually report the non-$CO_2$ impacts of their activities. The reporting results will be reviewed in 2027.

## Airspace considerations when scaling up contrail avoidance

Scaling up contrail avoidance reveals several potential challenges for airspace management, including potential reductions in airspace capacity due to safety concerns, increased airspace complexity, and higher workloads for air traffic controllers (ATCOs).

Avoiding contrail-prone areas could concentrate air traffic in other regions, possibly leading to congestion, especially in high-traffic zones. To balance traffic loads across sectors will require additional air traffic flow management measures. Safety and efficiency must remain paramount, and contrail avoidance measures must not compromise established safety protocols.

Operational contrail avoidance trials are crucial for understanding the real-life impact of contrail avoidance on ATM. Currently, to improve understanding of the climate impact of contrails and advance the development of potential solutions, contrail avoidance is performed on a targeted basis by a limited number of operators in Europe and in the United States. In the future, an opportunity may be available to deploy contrail avoidance at a wider airspace system level, requiring a contrail avoidance process flow initiated by ATC that centers around airspace considerations.

Contrail avoidance initiated at the ATM level must consider the impact on operations and procedures, coordination among sectors, capacity management, education and training, real-time atmospheric condition monitoring, data analytics, and the need for new advanced digital tools while maintaining the highest level of safety and efficiency in the aviation industry.

## Understanding the costs involved

The costs associated with contrail avoidance at scale in future airline operations can be divided into operational and capital expenditures. It is important to understand these costs in more detail to develop strategies and solutions for wide-scale adoption.

Based on findings from studies to date, implementing contrail avoidance causes a slight increase in fuel burn. Although additional research is needed, initial results suggest a 50% reduction in contrail length can be achieved with a 0.8% increase in fuel burn for the adjusted flights and an 80% reduction in contrail length with a 2% increase in fuel burn. Another trial showed a 54% reduction in contrail formation with a 2% increase in fuel burn. The fleetwide impact could be as low as a 0.1%–0.3% increase in fuel burn.[i]

Other operational costs to consider include increased flight duration, additional preflight planning, and pilot and dispatcher training. These costs are similar to those associated with existing procedures for avoiding turbulence. Software and personnel costs include upgrading flight planning and other systems, acquiring detailed weather predictions, and integrating machine-learning models. Additional dedicated personnel could also be needed to work on contrail avoidance.

For capital expenditures, equipping aircraft with humidity and temperature sensors could cost $50,000–$100,000 per aircraft, resulting in an industry-wide expenditure of $2 billion–$4 billion every 10 years. The ground-based, in-flight, and satellite-based observation infrastructure will also need to be improved. Using new satellite constellations could cost $3 billion–$4 billion every 10 years; however, newly deployed satellites would likely have additional uses, so these costs would not be fully allocated to contrail avoidance.

Amortized, the cost of avoiding contrails is preliminarily estimated to be from $1 to $6 per ton $CO_2e$ avoided, depending on the effectiveness of contrail avoidance and the chosen time horizon for the climate metric. It should be noted, though, that the calculation does not necessarily consider all future costs related to contrail avoidance.

If this cost is compared with the shadow price of carbon (SPC) and the social cost of carbon (SCC), which ranges from $200 to $1,100 per ton $CO_2e$, it suggests that contrail avoidance may be a highly cost-effective strategy for mitigating aviation's climate impact.

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**i** Research referenced includes Roger Teoh et al., "Aviation contrail climate effects in the North Atlantic from 2016-2021," Atmospheric Chemistry and Physics, March 30, 2022, **https://doi.org/10.5194/acp-2022-169**; Teoh et al., "Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption," ACS Publications, February 12, 2020, **https://doi.org/10.1021/acs.est.9b05608**; David Gelles, "Curbing Contrails: A Climate Solution in the Skies," *The New York Times*, August 8, 2023, **https://www.nytimes.com/2023/08/08/climate/curbing-contrails-a-climate-solution-in-the-skies.html**; and A. Martin Frias et al., "Feasibility of contrail avoidance in a commercial flight planning system: an operational analysis," *Environmental Research: Infrastructure and Sustainability 4*, no. 1, 2024, **https://iopscience.iop.org/article/10.1088/2634-4505/ad310c**.

## How to use this report

This report is divided into three major sections to clearly distinguish between what we already know (fundamentals), what stakeholders are working on right now (the present), and what lies ahead of us (the future).

**Section A: The Fundamentals — Contrail Impact, Management, and Modeling.** This section covers what we know about contrails, their climate impact, how contrails can be managed, and which models are available or in development to predict where warming contrails might appear.

**Section B: The Present — Addressing Uncertainty and Developing New Contrail Systems and Processes.** This section is about the ongoing work to increase the certainty of the climate impact of contrails and of prediction models. It provides an overview of research and trial activities taken by the aviation industry to date and of ongoing research projects and operational trials. It explains the contrail avoidance process flow and the work on establishing new processes with contrails being integrated into flight planning software and airline operational systems. Finally, considerations for developing MRV frameworks for non-$CO_2$ impacts are explored, including a discussion about appropriate metrics to use when comparing $CO_2$ and non-$CO_2$ climate effects.

**Section C: The Future — Contrail Avoidance Airspace Considerations and Costs.** This section examines possible future implications of contrail avoidance at scale at an airspace management level and discusses the potential cost parameters involved with broad application of contrail avoidance.

**Recommendations.** This content covers recommendations in support of actions to advance research and trials that can advance understanding of the climate impact of contrails and potential contrail management solutions.

## Collaboration

Lastly, this work would not have been possible without the engagement from participants of the Contrail Impact Task Force since its launch in November 2022. Addressing the climate impact of contrails presents challenges that can only be overcome through continued radical collaboration among stakeholders from across the aviation value chain.

# List of Abbreviations

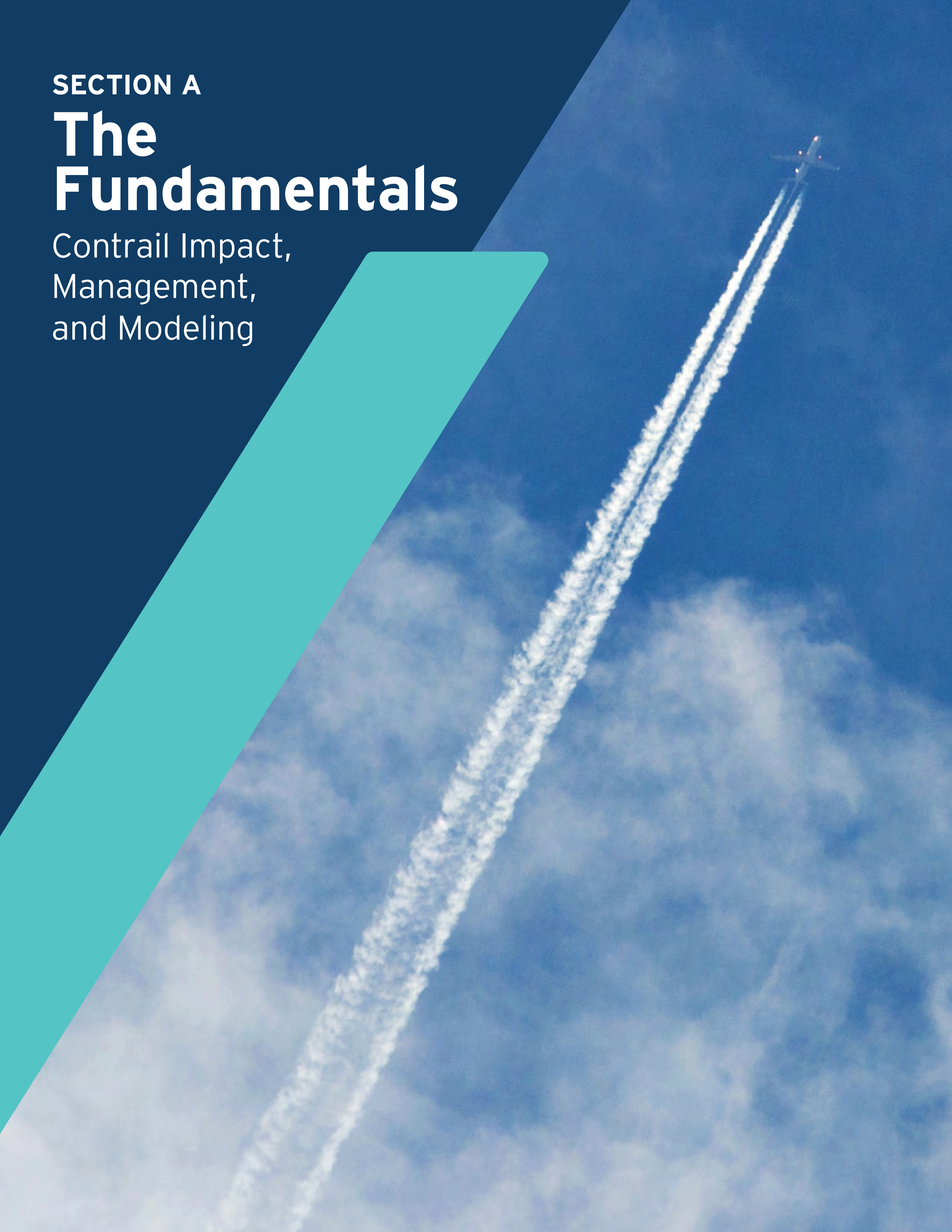
| | |
|---|---|
| **aCCFs** | Algorithmic Climate Change Functions |
| **ADS-B** | Automatic Dependent Surveillance-Broadcast |
| **AGTP** | Absolute Global Temperature Potential |
| **AGTP100** | Absolute Global Temperature Potential over a 100-Year Period |
| **AGWP** | Absolute Global Warming Potential |
| **AGWP20** | Absolute Global Warming Potential over a 20-Year Period |
| **AGWP100** | Absolute Global Warming Potential over a 100-Year Period |
| **AI** | Artificial Intelligence |
| **APCEMM** | Aircraft Plume, Chemistry, and Microphysics Model |
| **ARPA-E** | Advanced Research Projects Agency-Energy |
| **ATAG** | Air Transport Action Group |
| **ATC** | Air Traffic Control |
| **ATCO** | Air Traffic Controller |
| **ATM** | Air Traffic Management |
| **ATR** | Average Temperature Response |
| **CCI** | Cumulative Climate Impact |
| **CERM** | Contrail Evolution and Radiation Model |
| **CICONIA** | Climate Effects Reduced by Innovative Concept of Operations — Needs and Impacts Assessment |
| **$CO_2$** | Carbon Dioxide |
| **$CO_2e$** | Carbon Dioxide-Equivalent |
| **COA** | Certificates of Analysis |
| **CoCiP** | Contrail Cirrus Prediction Tool |
| **CONCERTO** | dynamicC cOllaboration to geNeralize eCo-friEndly tRajecTOries |
| **CORSIA** | Carbon Offsetting and Reduction Scheme for International Aviation |
| **DLR** | German Aerospace Center (*Deutsches Zentrum für Luft- und Raumfahrt*) |
| **ECLIF** | Emission and Climate Impact of Alternative Fuels |
| **EF** | Energy Forcing |
| **ERF** | Effective Radiative Forcing |
| **FAA** | US Federal Aviation Administration |
| **GHG** | Greenhouse Gas |
| **GPS** | Global Positioning System |
| **GTP** | Global Temperature Potential |
| **GTP20** | Global Temperature Potential over a 20-Year Period |
| **GTP100** | Global Temperature Potential over a 100-Year Period |
| **GWP** | Global Warming Potential |
| **GWP*** | Global Warming Potential Star |
| **GWP20** | Global Warming Potential over a 20-Year Period |
| **GWP100** | Global Warming Potential over a 100-Year Period |

| | |
|---|---|
| **HEFA** | Hydro-Processed Esters and Fatty Acids |
| **IAGOS** | In-Service Aircraft for a Global Observing System |
| **IATA** | International Air Transport Association |
| **ICAO** | International Civil Aviation Organization |
| **ICI** | Instantaneous Climate Impact |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ISSRs** | Ice Supersaturated Regions |
| **kg** | Kilogram |
| **MIT** | Massachusetts Institute of Technology |
| **MRV** | Monitoring, Reporting, and Verification |
| **MUAC** | Maastricht Upper Area Control Centre |
| **$mW/m^{-2}$** | MilliWatt per Square Meter |
| **$N_2O$** | Nitrous Oxide |
| **NASA** | National Aeronautics and Space Administration |
| **$NO_x$** | Nitrogen Oxides |
| **nvPM** | Nonvolatile Particulate Matter |
| **$nvPM_{num}$** | Nonvolatile Particulate Matter Number |
| **NWP** | Numerical Weather Prediction |
| **PRE-TRAILS** | Predictive Real-time Emissions Technologies Reducing Aircraft Induced Lines in the Sky |
| **PTWa** | Pump-to-Wake |
| **RF** | Radiative Forcing |
| **SAF** | Sustainable Aviation Fuel |
| **SAK** | Synthetic Aromatic Kerosene |
| **SCC** | Social Cost of Carbon |
| **SLCF** | Short-Lived Climate Forcer |
| **SPC** | Shadow Price of Carbon |
| **t** | Ton |
| **USD** | US Dollar |
| **WIMCOT** | Where Is My COnTrail |
| **WTP** | Well-to-Pump |
| **WTWa** | Well-to-Wake |
| **y** | Year |

SECTION A

# The Fundamentals

## Contrail Impact, Management, and Modeling



# 1. Introduction

## 1.1. Minimizing $CO_2$ and non-$CO_2$ in parallel

While this resource focuses on contrails and how to manage their climate impact, it is vital to see contrail management as part of a combined strategy for minimizing aviation's total climate impact, including carbon dioxide ($CO_2$) emissions and all non-$CO_2$ effects (not just contrails). Under no circumstances should the implementation of contrail management be a substitute for $CO_2$ emissions reduction or in any way pause advances in the scaling up of sustainable aviation fuel (SAF) adoption or any other $CO_2$ emissions reduction initiative. Minimizing aviation's $CO_2$ emissions and non-$CO_2$ effects must be done in parallel, never one to the exclusion of the other.

## 1.2. Existing industry efforts and tools to address aviation $CO_2$ emissions

The aviation industry is estimated to emit around 2% of global $CO_2$ emissions.[1] This percentage has been relatively stable since 1992. To align with the Paris Climate Agreement, the aviation industry has made a commitment to reach net-zero $CO_2$ emissions by 2050. The Air Transport Action Group (ATAG), a coalition of aviation industry experts focusing on sustainable development issues, has described pathways to reach net zero in the Waypoint 2050 report.[2] Likewise, the International Air Transport Association (IATA), the global trade association with 300-plus airline members, has committed to reaching net zero by 2050, which they plan to achieve by using different levers (see Exhibit 1), as described in IATA's Net Zero Roadmaps.[3]

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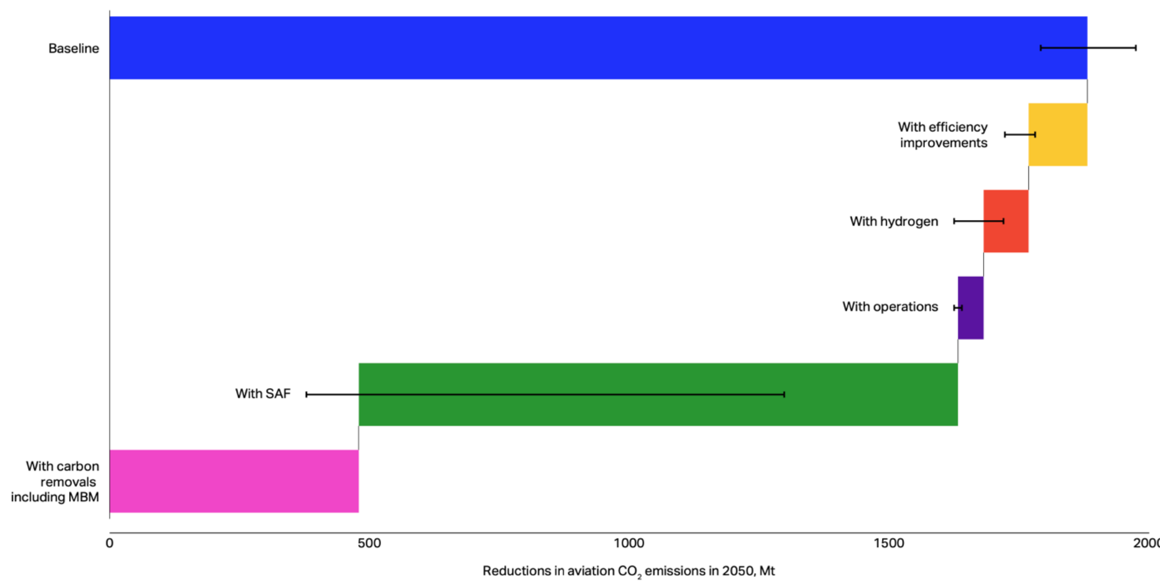
Exhibit 1

**IATA's Levers to Net Zero 2050**




Note: Reduction in aviation $CO_2$ emissions in 2050 achieved through the different levers of action. The solid bar indicates the central case, and the black lines indicate maximum and minimum reductions based on the scenarios modeled. Source: IATA

The industry plan is to use SAF as the biggest contributor to reducing $CO_2$ emissions, followed by efficiency improvements, hydrogen, and operational changes. In the end, the remaining $CO_2$ emissions will be addressed using carbon removals.

The International Civil Aviation Organization (ICAO), the United Nations specialized agency that oversees the aviation industry, has also adopted a collective goal for international aviation of net-zero $CO_2$ emissions by 2050. ICAO is pursuing aircraft technology improvements, operational improvements, SAF, and market-based measures (e.g., the Carbon Offsetting and Reduction Scheme for International Aviation, or CORSIA).[4]

SAF can greatly reduce well-to-wake (WTWa) emissions compared with conventional jet fuel. SAF production is expected to increase in the near-to-medium term, meaning airlines will be able to partner with engine manufacturers, SAF producers, and regulators to increase SAF's potential. The worldwide supply of SAF was 300 million liters (0.25 tons [t]) in 2022, which doubled to 600 million liters (0.5 t) in 2023 and is set to triple in 2024 to 1.875 billion liters (1.5 t), thereby covering a little more than 0.5% of aviation fuel needed.[5]

In 2021, United Airlines became the world's first commercial carrier to demonstrate the use of 100% SAF in one of two engines on a flight from Chicago to Washington, D.C.; and in 2023, Virgin Atlantic became the world's first commercial carrier to demonstrate the use of 100% SAF to fully power a flight across the Atlantic, from London to New York City.[6] These flights demonstrated that SAF is a safe drop-in replacement for fossil-derived jet fuel, advancing the market opportunity for scaled deployment.

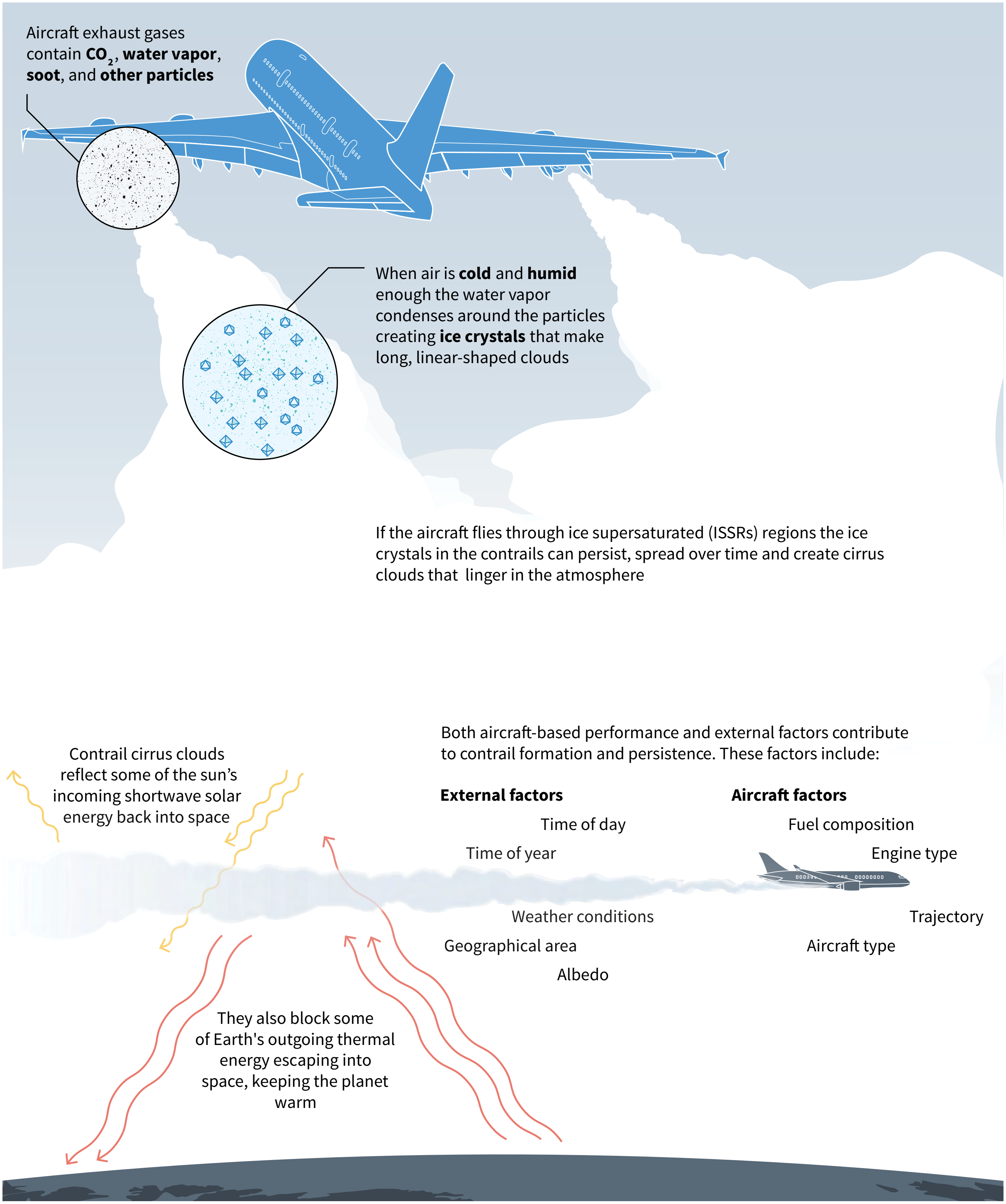
Additionally, advances in aircraft technology and fleet renewal over time will improve fuel efficiency and reduce the carbon footprint on a passenger-mile basis. Other tools, such as operational improvements (e.g., fewer layovers, flying more direct routes) and improved ATM systems, also have the potential to increase efficiency and reduce unnecessary fuel burn.[7]

Industry organizations have not yet published any reduction targets for aviation's non-$CO_2$ effects. They have, however, publicly recognized the existence of non-$CO_2$ climate impacts, such as nitrogen oxides ($NO_X$) and the net warming effect of contrails. In the spring of 2024, IATA published a contrail report, calling for more research into the location and climate impact of contrails.[8]

## 1.3. What are contrails, and how do they impact climate?

Condensation trails, or contrails, are the long line-shaped clouds that aircraft sometimes leave in the sky. When an aircraft burns jet fuel, it emits $CO_2$, water vapor, soot, and other particles. If the air is cold and humid enough, the water vapor condenses around the particles, creating ice crystals that make up the long white contrail clouds (see Exhibit 2). Most of these contrails disappear within a few minutes, but if the aircraft flies through an area with very cold and humid air — the so-called ice supersaturated regions (ISSRs) —the ice crystals in the contrails can persist, spread over time, and create high-altitude ice clouds, or cirrus clouds, which can linger in the atmosphere for hours.

## Exhibit 2 Contrail Formation and Warming Effects




RMI Graphic.

These artificial contrail cirrus clouds, created by the water and soot from aircraft exhaust, affect radiative forcing (RF), which is a measure of how the energy balance of Earth's atmosphere system is influenced: In the daytime, the contrail cirrus clouds reflect some of the sun's incoming shortwave solar energy back into space, cooling Earth. But contrail cirrus clouds also block Earth's outgoing long-wave thermal energy from escaping into space, keeping the planet warmer than it would otherwise have been. Contrails have a significantly higher warming impact at night when there is no heat from the sun to reflect into space, and the only climate effect the contrail clouds have is acting like a blanket, trapping heat on Earth.

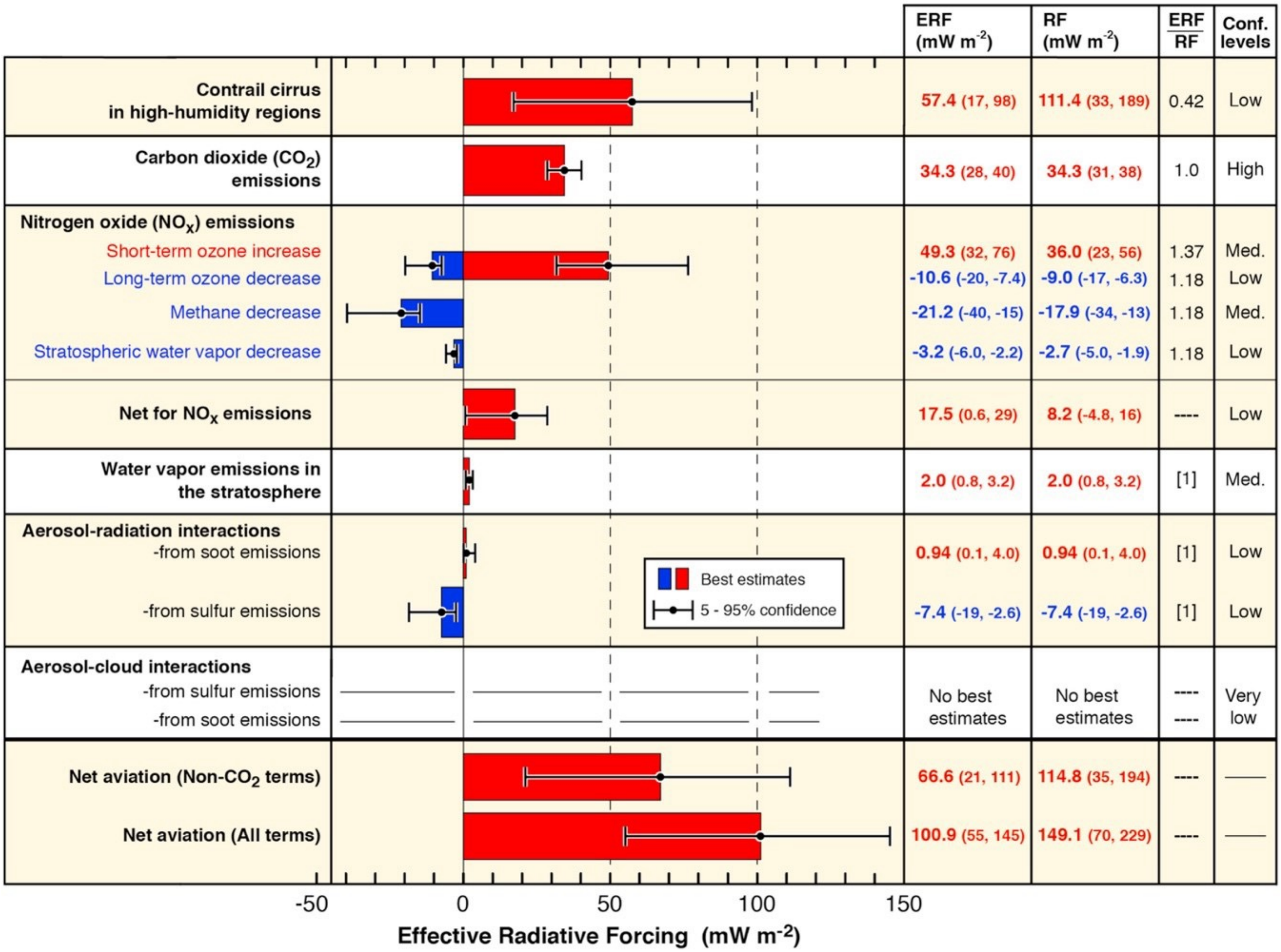
The climate impact of contrails varies greatly from flight to flight. Some flights can produce cooling contrails only, others warming contrails only. Some will produce a mix of warming and cooling contrails, and most flights will not produce any significant contrails because they do not fly through areas of cold and humid air. The contrail climate impact depends partly on internal factors like trajectory, aircraft and engine type, fuel composition, and other aircraft performance data, and partly on external factors like local weather conditions, time of day, time of year, geographical area, the albedo effect (the ability of surfaces to reflect heat from the sun), and more. Albedo has an impact because surfaces such as oceans and dense forests have a low albedo, meaning they do not reflect much of the solar radiation but absorb the heat instead, whereas sand- or snow-covered surfaces have a high albedo, meaning they reflect most of the radiation without absorbing heat.

Accurately estimating a contrail's total climate effect requires measuring its shape and optical properties at regular points during its life cycle and keeping the climate impact of the artificially created cloud separate from that of naturally occurring clouds in the area. Currently, because of the difficulty of obtaining these input values, there is relatively low certainty associated with estimating the climate effect of contrails, especially for a specific flight. Furthermore, predicting where persisting contrails may appear is challenging — especially because of the lack of detailed weather data at cruising altitudes and sufficient high-resolution satellite imagery needed to validate whether contrails were created and fed back to improve prediction models. In chapter 3, we discuss in further detail the need to increase certainties in contrails' climate impact and prediction models.

## 1.4. Estimating the impact of aviation's non-$CO_2$ effects

The non-$CO_2$ effects of aviation consist of NOx emissions, water vapor, aerosol-radiation and aerosol-cloud interactions from soot and sulfur, and the impact from condensation trails.[9] A quarter of a century ago, the Intergovernmental Panel on Climate Change (IPCC) wrote about the climate impact of aviation's non-$CO_2$ effects for the first time. In a special report on aviation from 1999, the IPCC estimated the RF from non-$CO_2$ effects to be a little larger than the RF from aircraft $CO_2$ emissions, with contrails being by far the biggest non-$CO_2$ contributor.[10] Exhibit 3, from a 2021 study, is often used to reference estimates of aviation's climate impact from both $CO_2$ and non-$CO_2$ factors.[11]

## Exhibit 3 **Global Aviation Effective Radiative Forcing (ERF) Terms**




Source: *Atmospheric Environment*

The bars show the best estimates for effective radiative forcing (ERF) from global aviation from 1940 to 2018,[ii] and the whiskers show values within the 5%–95% confidence intervals (the uncertainty span). Red bars indicate warming and blue bars indicate cooling. Although contrails have a much higher ERF than $CO_2$ emissions, the uncertainty span of contrails' climate impact is also significantly higher than $CO_2$. Within the uncertainty span, contrails could have half the ERF of $CO_2$ emissions in the lower end or more than 2.5 times the $CO_2$ emissions in the higher end. According to the 2021 study, $CO_2$ and non-$CO_2$ impacts from aviation are estimated to contribute a total of 3.5% (uncertainty range 3.4%–4.0%) of all human activities that drive climate change.

In another recent study, researchers simulated the global contrail climate forcing for 2019–21. They

**ii** The difference between ERF and RF is that ERF includes all tropospheric and land surface adjustments, whereas RF only includes the adjustment due to stratospheric temperature change (see **https://acp.copernicus.org/articles/20/9591/2020/acp-20-9591-2020.pdf**).

found that the global annual mean contrail net RF for 2019 (62 mW $m^{-2}$)[iii] was 44% lower than the best estimate for the 2021 study discussed above (111 mW $m^{-2}$).[12] However, the results were still well within the uncertainty bounds.

The new study also found that contrail RF is highly regional (see Exhibit 4). Europe (876 mW $m\text{-}^2$), the United States (414 mW $m\text{-}^2$), and the North Atlantic (300 mW/ $m\text{-}^2$) have the largest contrail net RF. East Asia (64 mW $m\text{-}^2$) and China (62 mW $m\text{-}^2$), which have seen rapid growth in aviation, are close to the global mean (62 mW $m\text{-}^2$) due to lower cruising altitudes where persistent contrails rarely form, and to limited ISSRs in the subtropics because of higher atmospheric temperatures at cruising altitudes. Therefore, airlines operating in certain geographies will generate higher contrail-induced warming relative to others.

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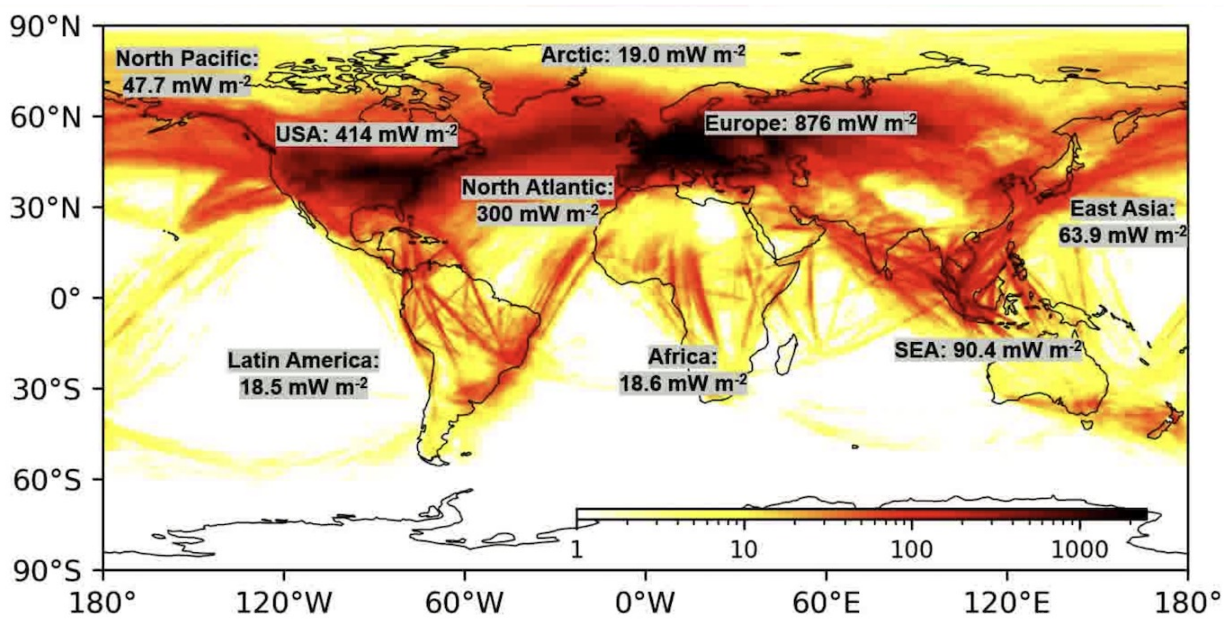
Exhibit 4

## Estimated 2019 Annual Mean Contrail Cirrus Net Radiative Forcing by Region




Source: *Atmospheric Chemistry and Physics*

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Furthermore, there are big differences in how $CO_2$ and persistent contrail cirrus warm the planet: While $CO_2$ has a very low immediate impact on global warming, the greenhouse gas (GHG) will persist in the atmosphere for centuries or millennia, and its impact will accumulate over time. With condensation trails, it is the opposite: The immediate climate impact of contrails is very high, but when the contrails clouds are gone after a few hours, so is their continued climate impact.

**iii** MilliWatt per square meter, or mW $m\text{-}^2$, is the unit used to measure RF. The numbers in the brackets show the upper and lower uncertainty bounds.

## 1.5. Contrail avoidance — a promising climate solution

Although scientists in the 1990s began to understand how persistent contrails can impact the climate, it was not until the 2010s that more researchers began to work on methods to avoid producing warming contrails and explore in detail the idea of flying around the cold and humid areas — the ISSRs — to avoid producing warming contrails.

The idea behind contrail avoidance — also called navigational contrail management or climate-optimized flight — is to use advanced computer models to predict where ISSRs will appear in the upper troposphere and then change the flight plans of aircraft scheduled to fly through the ISSRs. Instead, these flights will fly over, under, or around contrail-prone areas.

Revising the flight plan or trajectory to avoid contrails can sometimes increase fuel consumption and lead to higher $CO_2$ emissions. Therefore, it is important to ensure that the climate advantages outweigh the disadvantages.

Another approach is to target only the warming contrails and leave the cooling contrails in place. By letting aircraft fly regular, unadjusted trajectories during the daytime in areas where their contrails have a cooling effect while avoiding the biggest warming contrails (especially at night), the net climate effect of contrail avoidance is maximized.

Not all aircraft produce contrails, and not all contrails are warming. Several studies show that if we focus only on flights projected to produce so much warming that spending more on fuel and $CO_2$ emissions is justified to avoid the contrails, we need to adjust between 2% and 16% of flights, depending on geography, time of year, time of day, and weather conditions.[13] The same studies find that the climate effect of adjusting those flights is a reduction in contrail-induced warming of 54% to 80%.

The ability to analyze all flight trajectories for possible contrail-induced warming and recalculate flight plans to avoid contrails where it does not cost too much fuel and $CO_2$ is being built into some of the big flight planning software systems and is being used by aviation consultants and tech companies offering to help airlines manage their non-$CO_2$ effects.

The contrail prediction tools being used are currently challenged by the lack of humidity data required to accurately predict the location of ISSRs and the climate impact of the individual contrails that would be formed inside ISSRs. However, these predictions are expected to improve over time.

## 1.6. Alternative contrail management approaches

Although this report focuses on the application of contrail avoidance solutions, alternative approaches to contrail management are also being explored. These alternatives include the use of low-aromatic fuel (including SAF), hydrotreating of conventional jet fuel, engine technology improvements, and scheduling adjustments.

Along with humidity and temperature, nonvolatile particulate matter (nvPM) — and more specifically the non-volatile particulate matter number ($nvPM_{num}$) — within fuel exhaust streams contribute to contrail formation. Within fuel exhaust $nvPM_{num}$ varies based on engine thrust setting, fuel hydrogen, and aromatic content.[14] Changing one or more of these parameters can alter the potential formation of persistent contrails by changing the number of ice crystals formed.[15]

As aircraft engines continue to become more efficient, resulting in lower $CO_2$ emissions, these efficiency improvements may result in an increase in non-persistent and persistent contrails due to cooler exhaust plumes.[16] However, as less fuel is consumed, less nvPM is released. As described above, this reduction in $nvPM_{num}$ may potentially lower the life span of formed contrails and their resulting climate impact. Notably, on April 24, 2024, the US Federal Aviation Administration (FAA) finalized a rule setting standards for the maximum amount of nVPM emissions, including $nvPM_{num}$, from US civil aircraft engines, acknowledging the impact of nvPM on contrail formation, which provides aircraft manufacturers with certainty about emissions criteria for building next-generation engines.[17] However, engine efficiency improvements may take significant time to achieve, limiting their potential for reducing the climate impact of contrails in the near term. Additional research on this topic is needed to determine the full extent of the opportunity.

Preliminary research indicates that SAF — containing no aromatics — can reduce $nvPM_{num}$ by up to 70% compared with conventional fuels. This decrease in $nvPM_{num}$ is expected to reduce the overall lifetime and climate forcing potential of formed contrails.[18] Recent flight experiments show that burning low-aromatic SAF leads to a reduction in soot particle emissions and therefore a reduction in ice number concentrations in contrails.[19] This is because ice crystals grow slightly larger and sediment faster, which reduces the contrail lifetime and climate impact.[20]

Additionally, laboratory testing of fuel used for Virgin Atlantic Flight100[iv] showed that SAF produced from hydro-processed esters and fatty acids (HEFA) alone had a 70% reduction in the number of particulates, whereas the SAF blended from HEFA and synthetic aromatic kerosene (SAK) used for the flight had a 40% reduction in the number of particulates compared with conventional jet fuel.[21]

Other research, conducted in flight following an Airbus A350 as part of the Emission and Climate Impact of Alternative Fuels (ECLIF3) program, measured the effect of 100% HEFA SAF on particle emissions and contrail formation. This experiment found a 35% reduction in soot particle numbers and a 56% reduction in ice particle numbers compared with a cleaner than average Jet A-1 fuel.[22] Similar experimental evidence based on results from research conducted by the National Aeronautics and Space Administration (NASA) and DLR in 2018 found low-aromatic SAF can result in a 50%–70% reduction in soot and ice concentrations.[23] Ground testing research conducted in 2021 and 2022 by NASA, FAA, and Boeing as part of the ecoDemonstrator program also found adopting pure SAF or SAF blends results in substantial soot particle reductions at cruise power settings, which directly relate to ice crystal reductions.[24]

More research is needed to further explore and consolidate the results above. It should also be noted that the initial findings of these studies should not be used as blanket statements for the effects of SAF — and low-aromatic fuels in general — on contrail formation given the various SAF production methods and final composition of SAF products. In addition, although initial research results indicate an opportunity to strategically deploy SAF along routes with greater potential for forming contrails, consideration must be given to the impact such an approach could have on the emerging SAF market.[25] Further research should be conducted prior to deployment decisions based on this topic.

Hydrotreated Jet A-1 fuels may also reduce aviation's non-$CO_2$ effects based on the lower aromatic content of processed fuels, which may reduce the life span and climate impact of formed contrails.[26] Hydrotreating becomes an even more appealing option considering fuel cost savings as well as reduced GHG emissions due to higher energy intensity compared with regular Jet A-1.[27] Notably, however, today hydrogen is

**iv** On November 28, 2023, Virgin Atlantic became the first commercial airline to operate a 100% SAF powered flight on a transatlantic route, from London to New York City.

predominantly produced using fossil fuel–based processes, and is known as grey hydrogen. When considering additional hydrotreating for the purpose of reducing non-$CO_2$ effects of aviation, upstream carbon intensity should be accounted for because additional emissions from hydrogen production may offset the benefits from reductions in warming contrails. Lower carbon intensity green and blue hydrogen should be considered in this case for additional hydrotreating applications. However, production methods for green and blue hydrogen are currently more expensive than traditional grey hydrogen production methods. Therefore, further research should be conducted to explore the upstream and downstream effects of hydrotreated Jet A-1 on contrails.

Lastly, contrails have the most significant warming potential during cooler months, during nighttime hours.[28] Adjusting flight schedules to accommodate more daytime flights during certain times of the year along contrail-prone routes could be explored to help reduce warming contrails. However, this alternative is largely considered to be impractical because it faces significant constraints such as airport capacity and air traffic capacity. Compressing flight schedules into shorter daily operating windows would likely reduce operations overall, given the priority to ensure flight safety. Given shorter daylight hours in cooler seasons in particular, adjusting flight schedules to avoid nighttime contrail formation could result in significant reductions in flight operations and air service offerings. Flights to avoid nighttime travel may also be prohibitive because of the need to arrive at the destination airport within specific hours according to airport policies. These challenges reduce the practicality of this alternative to be applied widely by commercial operators. However, private operators may be better positioned to adjust operations given their greater operating flexibility. Additional research on this alternative is needed to understand the full impact of scheduling adjustments on airport and airspace capacity as well as on airline operating procedures and costs.

A combination of contrail management solutions will likely be necessary to recognize the full extent of the opportunity to reduce the climate impact of contrails.

## 1.7. The present status of contrail management and contrail-related science

Most ongoing research efforts related to contrails focus on three main themes:

1. Increasing certainty of the climate impact of contrails: Currently, we know that the warming effect of contrails could be half the impact of aviation's $CO_2$ emissions, but it could also be about three times higher than that of $CO_2$ emissions. This uncertainty makes it difficult to estimate the full climate impact of aviation and difficult to accurately quantify the savings from contrail avoidance activities.

2. Increasing prediction model accuracy: Efforts are underway to improve prediction models. They need more validation data from ground-based cameras, in-flight observations, and satellite-based observations to be able to verify if they correctly predicted the making or the avoidance of a contrail. This data will feed back into the models and improve them over time. There are also projects in development to equip planes with humidity sensors, enhance satellite imagery, and get better weather inputs, which also have potential to make prediction models more accurate.

3. Learning from operational trials, including airspace considerations: There are two main approaches to operational contrail avoidance trials. One is government-funded, multiyear projects involving key stakeholders across the aviation value chain, such as the European-initiated Climate Effects Reduced by Innovative Concept of Operations — Needs and Impacts Assessment (CICONIA) project.[29]

Alternatively, privately funded projects involving fewer targeted stakeholders are conducting flight trials within shorter timelines — spanning from project ideation to completion in a matter of months instead of years — resulting in quick output and learnings. An example of this trial type was demonstrated by American Airlines, Google Research, and Breakthrough Energy in 2023.[30] Both approaches can lead to valuable results and learnings, and both are critical for the advancement of contrail science.

In chapters 3 and 5 of this paper, we go into more detail on all three themes.

Researchers are also focusing on future solutions such as estimating potential reductions in warming contrails for various types of SAF, the impact of revolutionary engine technologies on contrail-induced warming, and contrails formed by hydrogen-powered aircraft.

# 2. Contrail Prediction Modeling

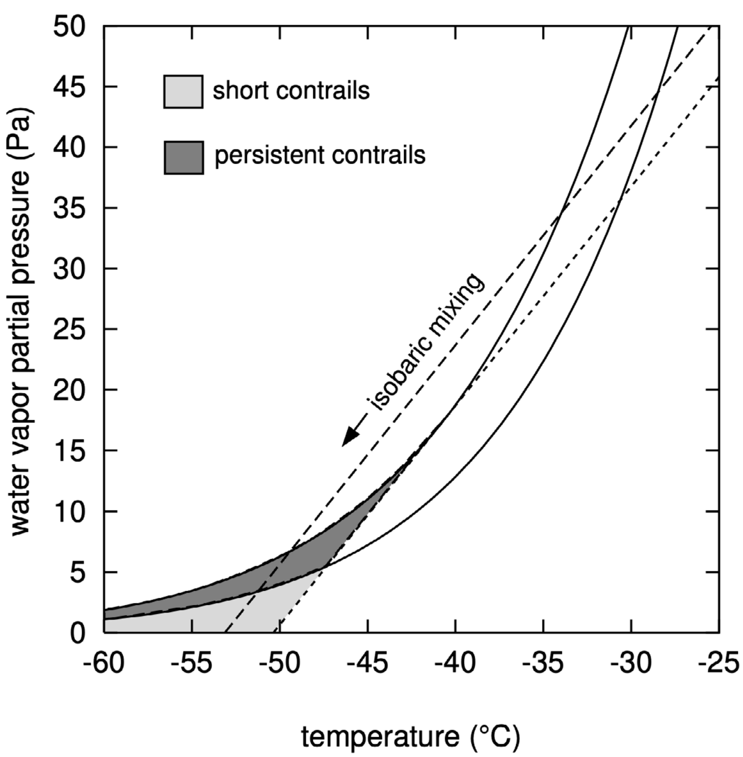
Contrail prediction modeling consists of forecasting when and how contrails will form behind aircraft, their characteristics, and ultimately their impact on climate. Several prediction models have been developed in the past by various research institutes. They are used not only to retroactively determine if contrails were generated by a set of flights but also to inform future flight paths and operational strategies that could minimize or avoid contrail generation altogether, thereby reducing aviation's contribution to climate change. As discussed above, estimating the climate impact of contrails currently has high uncertainty. The ultimate climate impact value carries a cascade of uncertainties deriving from weather data, aircraft performance, atmospheric interactions, and cloud properties.

## 2.1. How do we know if a contrail will form and if it will persist?

Contrails form behind aircraft when the surrounding air mass is cold and humid enough. The soot produced by the aircraft, along with the surplus of water vapor in the exhaust, triggers a condensation process that leads to visible water in liquid and then solid form.

The physical criteria defining whether a contrail will form is called the Schmidt-Appleman criteria, as illustrated in Exhibit 5.

Exhibit 5 **Schmidt-Appleman Criteria**




Source: Meteo-France

The Schmidt-Appleman criteria looks at water vapor partial pressure and temperature. As the engine exhaust follows a theoretical isobaric mixing (dashed line), temperature drop leads to a decrease of water vapor partial pressure. If the water vapor partial pressure becomes superior to the saturating level with respect to liquid water (upper curve), water vapor may condense around soot or aerosol particles originating from the engine exhaust. As pressure and temperature drop more, the water droplets freeze and form a linear cloud behind the aircraft. If the pressure and temperature values keep dropping, the cloud will only be short-lived, also called a short contrail. However, if thermodynamically, the final pressure and temperature end up in an area located between the two curves (1) saturating water vapor pressure with respect to liquid water and (2) saturating water vapor pressure with respect to ice, then the contrail cloud will initially persist.

During a November 2023 conference, Météo-France presented a graphic illustrating the different cases for short-lived or persistent contrails to form (see Exhibit 6):

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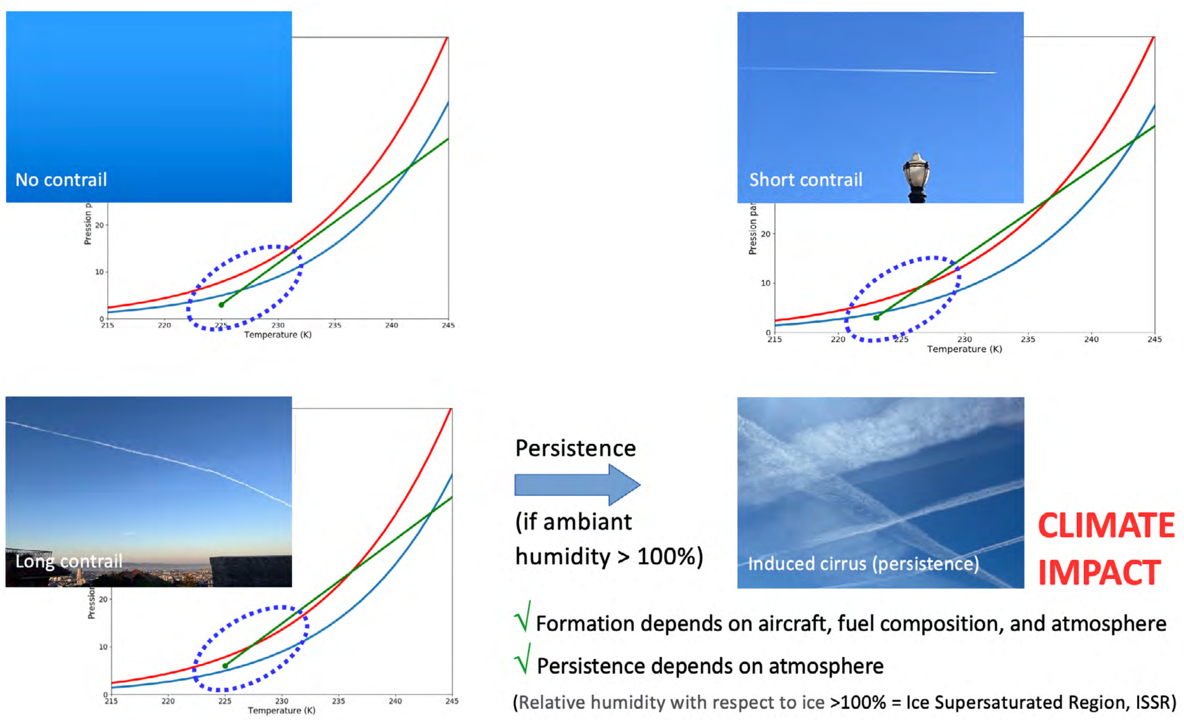
## Exhibit 6 Examples of Short-Lived and Persistent Contrails




Source: Meteo-France and Institute for Sustainable Aviation

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This initially persistent contrail cloud is an anthropogenically induced cirrus, "activated" by an airplane passing through the air mass. It then becomes subject to wind and other local air mass characteristics that affect its evolution.

## 2.2. Models for contrail prediction

Although several contrail prediction models exist, each tailored to model specific aspects of contrail formation and impact, two models are currently widely used within the industry: the Contrail Cirrus Prediction tool (CoCiP) and the Algorithmic Climate Change Functions (aCCFs). This section analyzes in detail the methodologies used by these models and introduces other new or alternative models.

### 2.2.1. Contrail cirrus prediction tool and Pycontrails

CoCiP was developed by Ulrich Schumann from DLR.[31] CoCiP is a weather-based model that uses a Lagrangian approach. The model is based on analyzing flight trajectories and surrounding weather data. It can be broken down into three steps:

1. Analyzing whether a contrail will be formed behind the aircraft according to the Schmidt-Appleman criteria and whether that contrail can persist or not

2. If persistent, estimating the contrail lifetime and physical parameters: the ice particle size and density as well as the width, length, and thickness of the plume that forms behind the aircraft

3. Integrating the radiative forcing of the plume at any given time across all dimensions to produce an EF value associated with the flight

CoCiP virtually follows the aircraft flight profile and the contrail evolution after its initial generation, long after the aircraft passed by.

Initially coded in Fortran, the team of Marc Stettler and Roger Teoh from Imperial College London, along with a team at Breakthrough Energy led by Marc Shapiro, gradually adapted CoCiP into a Python package called Pycontrails. Pycontrails is today widely used by the industry and is meant to include models beyond CoCiP.

Pycontrails CoCiP remains the main model-based approach for monitoring and forecasting contrails. It is widely used in the industry by companies including Airbus, Boeing, Estuaire, and Eurocontrol, and by flight planners FLIGHTKEYS and Lido, either directly or via a provider that runs the model on its premises. Large airlines such as American Airlines, Air France, and EasyJet have also based their contrail mitigation efforts on CoCiP. NASA's Ames Research Center also leverages CoCiP outputs in its contrail simulation model.[32]

The advantages of CoCiP are that it does not require a lot of computing effort, making it a good candidate to analyze thousands of flights in minutes. At the same time, it also captures a lot of parameters, such as engine or aircraft type, weather, and time of day, enabling the user to single out individual flight contributions to contrail formations.

It also exhibits several areas for improvement:

- Its accuracy depends on the quality of weather inputs. So far, predicting accurate ISSR at high tropospheric levels is difficult.

- The validation of CoCiP was initially performed by Schumann himself using ground-based observations (see chapter 3). Many efforts are under way to complement these observations.

- CoCiP requires an aircraft performance model to estimate the thrust setting of the aircraft and characterize emissions. There are existing private and free use aircraft performance models that are being used, but they have limitations. Schumann and Poll developed a new model that can be used to calculate engine efficiency for inputs needed for the CoCiP model. Ultimately, all models are fit for purpose but vary in aircraft type coverage and conditions of use.

- CoCiP advertises a high sensitivity to aircraft black carbon emissions, or nvPM. These particles act as condensation nuclei for ice to form at altitudes. Past modeling studies and recent flight trials (see chapter 4.1) have highlighted that other particles such as lubrication oil or ions might play a role as condensation nuclei.[33] CoCiP might overestimate a modern, low nvPM aircraft engine as a low contrail producer.

- CoCiP also considers an infinite humidity budget, meaning that the formation of one contrail cloud does not reduce the amount of humidity available to produce another cloud. This issue can be partially addressed by considering an efficacy factor to account for the proper climate impact (i.e., the delta of temperature or ERF instead of RF)

Despite those drawbacks, the model's ability to receive improved input parameters needs to be highlighted. Setting a humidity budget, considering other nucleation particles, and feeding it with improved relative humidity data are current areas of research.

### 2.2.2. Algorithmic climate change functions

aCCFs are a set of mathematical functions,[34] also built by DLR, with a "climate approach" to contrails, differing from the "weather approach" of CoCiP. They were built using a top-down approach, starting from global climate model simulations and a reduced climate response model such as AirClim, cascading down a global climate response to individual contrail generation events.

aCCFs are mathematical formulations that aim to estimate the climate effect of a point source of emissions. An aCCF exists for contrails and for other types of aircraft emissions, including nitrogen oxides (NOx) induced ozone emissions, $CO_2$, and water vapor emissions.

The first step is using the Schmidt-Appleman criteria to understand if an initially persistent contrail will likely form. For this, an aircraft performance model and humidity and temperature data are also required. Once the model determines the persistence of the contrail, then the aCCF is applied to compute the warming effect of that individual contrail. Two aCCFs exist for contrails, one for daylight and the other for nighttime. The main parameters considered are:

- The outgoing longwave radiation, which is deduced from the time of day and position on the globe

- The temperature

Contrail aCCFs provide a rapid way of estimating contrail RF. However, they show limitations that DLR is currently addressing:

- Validity for the Northern hemisphere only with a focus on Europe.

- Climate impact is expressed in $CO_2$ equivalent ($CO_2e$) using an average temperature response (ATR) metric over 20 years (ATR20 metric). Work is ongoing to express the output in $CO_2e$ using a global warming potential (GWP) over a 100-year period (GWP100).

aCCFs are one of the fastest ways to analyze a large set of flights. However, as a top-down approach derived from a climate model, some parameters are not considered, such as engine and aircraft type characteristics, nvPM emissions, and physical evolution of the contrail in the atmosphere (geometry, lifetime, change of Earth background surface).

### 2.2.3. Contrail Evolution and Radiation Model

The MIT Laboratory for Aviation and the Environment developed the Contrail Evolution and Radiation Model (CERM). It is very similar to the early versions of CoCiP, considering flight trajectories and weather parameters as the main inputs and following a Lagrangian approach.

According to its founding paper,[35] many publications from DLR were used to build the first version of CERM when CoCiP was not publicly available in its Python version and lacked validation. The model continues to be used by some researchers but is not publicly available.

### 2.2.4. Aircraft Plume, Chemistry, and Microphysics Model

The MIT Laboratory for Aviation and the Environment also developed the Aircraft Plume, Chemistry, and Microphysics Model (APCEMM).[36] Written in C++, APCEMM aims to model the evolution of the plume behind an aircraft. APCEMM was recently adapted to better describe the ice nucleation process behind an aircraft and visualize the formation and evolution of that cloud in three dimensions.

The very fine description of the contrail can be used to characterize the RF of any portion of air mass that an aircraft crossed. This RF can then be aggregated to derive a global climate impact value.

The main limitation of APCEMM is its relatively limited ability to scale compared with CoCiP because it requires greater computing power to be run on several flights. It is also subject to the same input data quality issues as other models, notably humidity, wind, and aircraft performance.

### 2.2.5. Machine-learning contrail forecasting

Recent research initiatives explore contrail prediction models based on artificial intelligence (AI).[1][2] These models do not rely on complex physics modeling of the phenomena driving contrail formation but rather rely on neural network models to link flight tracks and reanalyzed weather data with persistent contrail observations identified on satellite images. The process is as follows:

1. First, contrails are detected on geostationary satellite images using AI models.
2. Then, contrails are associated with historical flight tracks thanks to a matching algorithm.
3. Reanalyzed weather data is interpolated along the historical flight tracks.
4. Weather statistical parameters are computed and gathered with exogenous data on the flight (latitude, longitude, altitude, solar radiation) to create a set of input parameters.
5. Finally, a neural network model is trained to predict if a persistent contrail was generated based on the input parameters.

Ultimately, both observations and forecasts based on this approach can be made available, including:

- Machine-learning–based observations: A database of contrail detections plus flight attribution that could be used to evaluate the efficacy of an avoidance regime.
- Machine-learning–based forecasts: Grid-based contrail forecasts that contain a probability of formation along with the energy forcing (EF) of a formed contrail.

This approach is currently being investigated by Google Research in its Project Contrails.[37]

Although the performance capabilities of this type of model are still unknown, this type of model could prove useful by:

- Overcoming the uncertainty in high-altitude weather parameters of current numerical weather prediction (NWP) models, because the neural network would learn and process weather predictions accounting for the limited accuracy of the weather data.
- Simplifying the modeling by not relying on physics assumptions that are either too complex or too simple.

Expected limitations might be:

- Too little information on the predicted contrails: binary prediction with no information on contrail characteristics such as EF and lifetime.
- Limited ability to explain contrail predictions.

### 2.2.6. Other models

Google Research and Breakthrough Energy have developed a prototype ensemble contrail forecast model that uses a combination of an observation-based contrail formation model and physics-based contrail impact model to predict high-probability high-climate forcing contrail outbreak regions.

Several other models also concentrate on forecasting the formation of contrails and assessing their impact on the climate. This group includes, but is not limited to, models such as AirClim, LinClim, OSCAR, LEEA, and FaIR. These models (see Exhibit 7) were introduced during the Non-$CO_2$ MRV Consultation, led by a consortium of consultancy To70, software developer AerLabs, and scientists from DLR in December 2023. Detailed information about these models remains somewhat limited.[38]

## Exhibit 7 Models and Input Data for Contrail Prediction

| Models/input data | CoCiP (Pycontrails) | aCCFs | AirClim openAirClim | FAIR | OSCAR | LEEA | Fuel Burn Module | Emissions Calculation Model |
|---|---|---|---|---|---|---|---|---|
| | **Flight trajectory** | | | | | | | |
| Timestamp | ✓ | ✓ | | | | | ✓ | ✓ |
| Latitude | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Longitude | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Altitude | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| True airspeed | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | **Meteorological data** | | | | | | | |
| Pressure | ✓* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Air temperature | ✓* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Specific humidity | ✓* | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Relative humidity over ice | | ✓ | | | | | | |
| Eastward wind | ✓* | | | | | | ✓ | |
| Northward wind | ✓* | | | | | | ✓ | |
| Vertical velocity | ✓* | | | | | | | |
| Specific cloud ice water content | ✓* | | | | | | | |
| Geopotential | ✓* | ✓ | | | | | | |
| Outgoing longwave radiation (OLR) | ✓* | ✓ | | | | | | |
| Reflected solar radiation (RSR) | ✓* | | | | | | | |
| Solar direct radiation (SDR) | ✓* | ✓ | | | | | | |
| | **Aircraft properties and performance** | | | | | | | |
| Aircraft type | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Engine Unique Identifier (UID) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Fuel flow | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Aircraft mass/Takeoff mass/Load factor** | ✓ | | | | | | ✓ | |
| Engine efficiency | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | |
| | **Fuel properties & SAF** | | | | | | | |
| Hydrogen content | ✓ | ✓ | ✓ | | | | | |
| Calorific value | ✓ | | | | | | | |

* These meteorological data are needed 3-dimensional ( 2-dimensional for the radiation variables) and time-dependent (not only along the trajectory)

* * Either aircraft mass along the trajectory or takeoff mass or load factor is needed

RMI Graphic. Source: Adapted from the Non-$CO_2$ MRV Consultation Meeting

## 2.3. Inputs required for contrail prediction modeling

For any model, whether it is physics-based or not, the prediction performance is highly dependent upon the data quality of the input parameters. The required input data, however, varies with the model used.

For physics-based models like CoCiP, the required input parameters can be split into three categories. The required parameters specific to CoCiP are:

1. Flight trajectories
   - Time, latitude, longitude, and altitude
2. Aircraft and engine type and parameters
   - Engine efficiency to evaluate the Schmidt-Appleman criteria
   - nvPM emissions to estimate contrail initial properties. In the implementation of CoCiP in Pycontrails, this can involve estimating the engine non-dimensional thrust setting to interpolate nvPM data in the ICAO Aircraft Engine Emissions Databank
   - Engine fuel burn to estimate the mass of water vapor exiting the engine, the total amount of nvPM emissions, and the change in aircraft mass through the flight
   - Aircraft characteristics, such as aircraft mass, airspeed, and wingspan, to simulate the downwash evolution of a contrail in the wake vortex of the aircraft
3. Fuel characteristics
   - Fuel hydrogen-to-content ratio
   - Amount of sulfur or aromatic compounds
   - Lower calorific value
4. Weather data derived from NWP

   **(a.)** Four-dimensional parameters (latitude, longitude, altitude, and time):
   - Relative or specific humidity
   - Temperature
   - Wind
   - Geopotential height
   - Atmospheric pressure
   - Cloud ice-water content

**(b.)** Three-dimensional parameters (latitude, longitude, and time):

- Top of the atmosphere solar radiation to estimate the solar energy reflected to space by a contrail
- Top of the atmosphere thermal radiation to estimate the thermal energy trapped by a contrail in the atmosphere

### 2.3.1. Data gaps and default values

For the four categories of data above, some often-encountered data gaps can limit the accuracy of the models:

1. Flight trajectories can be retrieved from flight data recorders published automatic dependent surveillance-broadcast (ADS-B) sources. When ADS-B sources are used, lack of coverage of certain areas can be an issue. Flight points interpolation can be a remedy if the gaps are small enough and the flight trajectory is expected to be constant. When FDRs are used as a source of trajectories, more waypoints are recorded, and other information, including aircraft mass and real fuel flow, are available. However, coverage or quality issues can arise as well. Flight data recorder information is also harder to obtain and to clean because of heterogeneous sources coming from different aircraft. Ultimately, using a combination of ADS-B sources and FDRs can provide a full coverage of flights.

2. Aircraft and engine parameters are often difficult to estimate accurately without access to proprietary data of original equipment manufacturers and airlines:

   - If direct aircraft performance data is not available, a default value between 0.2 and 0.35 for engine efficiency can be used, depending on the engine technology
   - Few measurements of particle emissions of aircraft engines during flight exist. The ICAO Aircraft Engine Emissions Databank provides an overview of sea- level emissions indices for various thrust settings, but these emissions need to be extrapolated to the flight situation.

3. Several NWP models exist today. They can be divided into models that analyze past weather data, known as reanalyzed models, and those focused solely on forecasting future weather. The latter look at future weather conditions from an initial set of weather conditions. The future conditions are governed by atmospheric laws and simulated over a gridded atmosphere. The size of the grid, the density of initial observations, and the atmospheric laws used have an impact on the accuracy of weather parameters. NWP modeling employs a system of models to calculate the dynamics of the atmosphere, radiation, and meteorology, including cloud formation, to predict atmospheric conditions. Initialized with observations of the atmosphere, NWP modeling integrates a suite of algorithms to predict how initial conditions will evolve over time and space. When used in contrail modeling, the weather data output from the NWP model is critical because whether a contrail will persist (and thus whether the tools such as CoCiP may be needed to track the contrail) depends on the model's pressure, temperature, and water vapor predictions. Benchmarking state-of-the-art NWP models against physical measurements is key to validating humidity predictions in high altitude. This humidity data validation exercise was conducted by Imperial College London on the European Centre for Medium-Range Weather Forecasts' ERA5 data set (an historical reanalyzed forecast). Private companies such as Excarta and SATAVIA are developing their own NWP models to improve

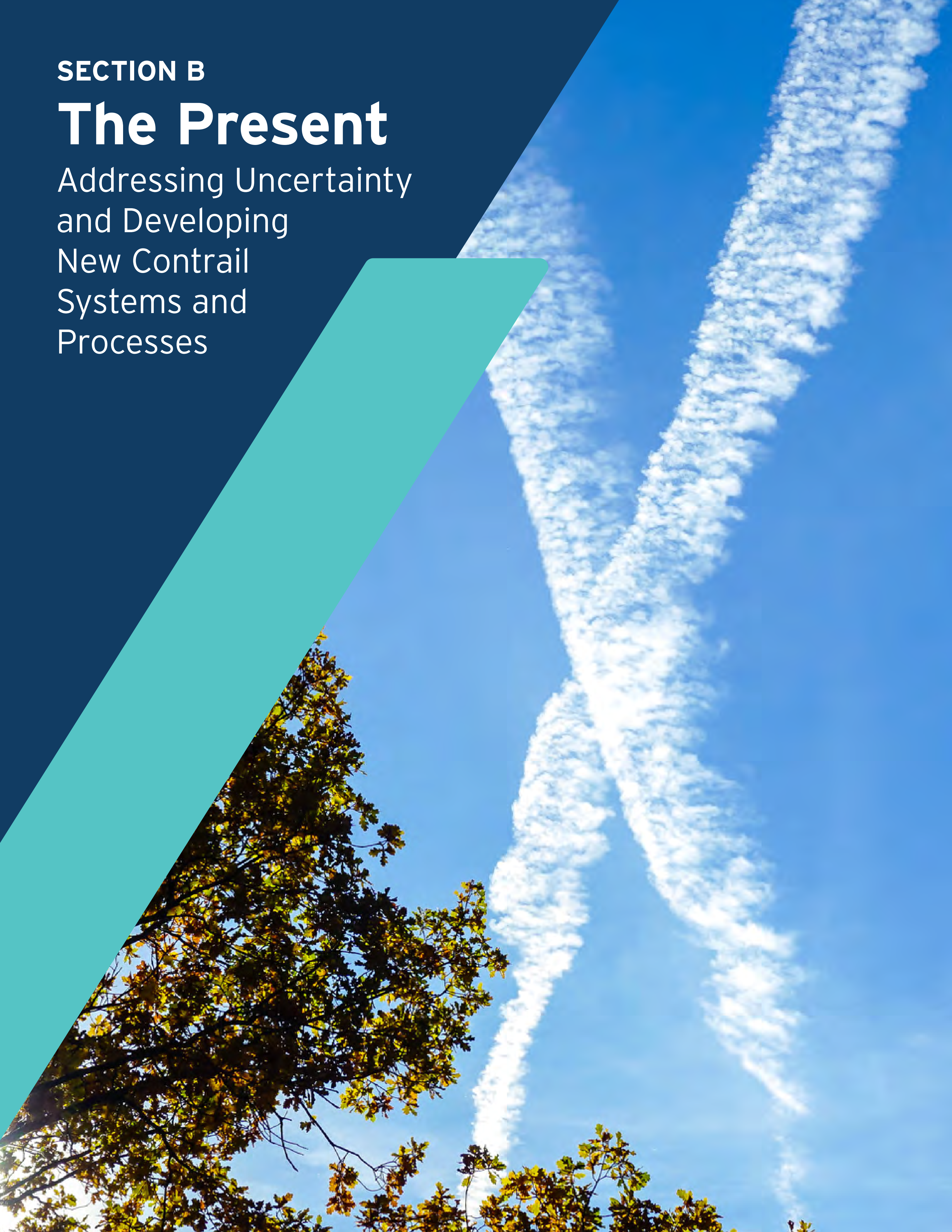
relative humidity forecast. Historically, aviation has often relied on a combination of weather models, dynamically selecting the most fit for the area of interest (e.g., the eWAS app). The future of contrail avoidance could be similar.

4. Although initial research has been done to better understand the contributions of volatile particles and the impacts of fuel compositions on contrail formation, additional research is needed — especially under low-soot emission engine operating conditions — to help improve prediction models.

**SECTION B**

# The Present

## Addressing Uncertainty and Developing New Contrail Systems and Processes



# 3. Addressing Uncertainties of Contrail Impact and Avoidance

## 3.1. Climate impact uncertainties

### 3.1.1. Trade-offs between contrail-induced warming and $CO_2$ emissions

The climate impact of contrails is understood to be significant, estimated to range from half to over three times that of $CO_2$ emissions from aviation activity.[39] But it is difficult to confidently quantify the potential benefit of contrail management due to uncertainty about the effect contrails have on the climate. Additionally, not all contrails are created equal.[40] The EF of a contrail formed on one flight may be significantly different than that of another, depending on factors such as seasonal considerations, time of day, atmospheric conditions — including temperature, humidity, and wind at the time of flight and afterward — aircraft performance, fuel composition, etc. Accounting for all these factors as well as contrail climate impact uncertainty make it difficult to determine whether taking action to avoid a contrail will result in a net climate benefit (see Exhibit 8).

Calculating aircraft fuel burn and associated emissions is standard practice in the aviation industry. To conduct trajectory-based contrail avoidance, these calculations must be thoughtfully considered. Prediction modeling tools enable the ability to avoid contrails, but that does not mean that all predicted contrails should be avoided. Because the climate impact of contrails varies from one flight to another, the impact of fuel burn required to alter a flight trajectory also varies, making it difficult to determine the net warming reduction from one flight to another when contrail avoidance is applied.

Although trials and simulation results to date indicate that flight trajectories optimized for contrail avoidance can be achieved with minimal additional fuel burn — as low as 0.11% for the optimized flights based on simulations conducted in 2023[41] — the warming impact of additional fuel burn and associated $CO_2$ emissions must be compared with the potential to reduce contrail-induced warming. To improve confidence in contrail-induced warming reduction potential, additional data and research are needed to verify the effectiveness of prediction models and increase certainty about the climate impact of contrails. Additionally, the aviation industry needs to adopt a standard metric to quantify contrail impacts. Details of potential metric options are discussed in chapter 4.

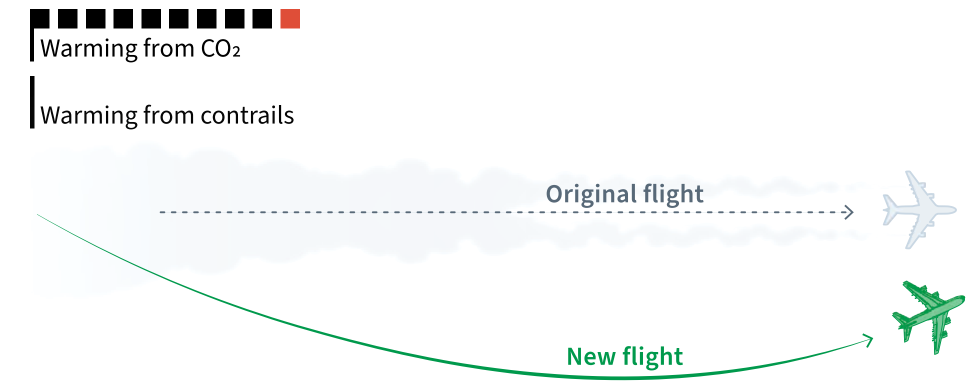
## Exhibit 8 **Trade-offs between Contrail-Induced Warming and $CO_2$ Emissions**

### Base scenario

An aircraft is responsible not only for the **$CO_2$ it emits** but also for the warming it produces by flying through cold and humid areas, creating **persistent contrails.**

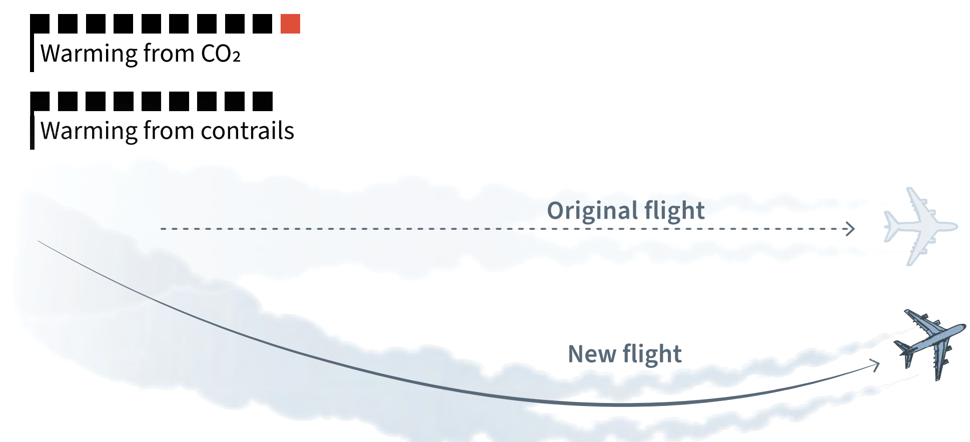

### Scenario 2

The aircraft trajectory is adjusted to **avoid the contrail areas**, and the avoidance is successful: The aircraft uses a little more fuel and releases a **little more $CO_2$** to change altitude, but the climate savings from the avoided con-trails provide a substantial climate **net benefit.**




### Scenario 3

The aircraft trajectory is adjusted to avoid the contrail areas, but the aircraft still **produces a contrail** while using more fuel and **releasing more $CO_2$** to change altitude.




RMI Graphic. Source: RMI analysis

### 3.1.2. Differences in research and modeling at the aviation system level vs. individual flight impacts

Given the current accuracy of contrail prediction models, assessing the contrail climate impact of a single adjusted flight is highly uncertain. Therefore, it can be beneficial to measure the impact of many flights over a period so that more wholistic total and average impact numbers can be calculated.

Although additional research is needed to reduce uncertainty associated with the climate impact of contrails and critical improvements are needed to increase contrail prediction modeling accuracy — such as more reliable humidity data at cruising altitudes — large-scale modeling simulations conducted to date indicate the promising opportunity for navigational contrail avoidance strategies to reduce contrail EF. For example, research conducted in collaboration between FLIGHTKEYS, Breakthrough Energy, Universidad Carlos III de Madrid, and Imperial College London identified significant reduction in total contrail EF by optimizing flight plans to avoid warming contrails. The study simulated a total of 84,839 flights over two 15-day periods in June 2023 and January 2024. Of the flights identified as appropriate for optimization based on a set contrail EF threshold, cumulative contrail EF was reduced by approximately 73% at a total cost increase of 0.08%, an increase in fuel burn of 0.11%, and no change in total flight time. Measuring the net warming reduction from contrail-optimized flights accounting for additional $CO_2$ emissions from associated fuel burn, results found a $CO_2e$ reduction of 7.6% calculated on a GWP100 basis and a reduction of 22% calculated on a GWP20 basis.[42]

These modeling results show a significant opportunity on a cumulative basis, for flights that are forecast to produce warming contrails. However, it may not always make sense to implement avoidance because doing so could require excessive fuel burn. In other words, regardless of the forecast contrail-induced warming severity, flights should not be considered eligible for contrail optimization if the fuel burn required to do so would result in warming from $CO_2$ emissions greater than the potential warming reduction from contrail avoidance. To make this determination, the metric used to assess contrail-induced warming reduction plays a critical role. For a detailed assessment of this topic, see chapter 4.

Additionally, the aviation industry needs to identify an appropriate methodology for baselining contrail impact that at a minimum accounts for regionality and seasonality. As shown in Exhibit 3 (page 22), in 2021, global average contrail RF from global aviation between 1940–2018 was estimated to be 111.4 mW $m^{-2}$.[43] In 2023, using reanalysis weather data and actual flight trajectory data sourced from ADS-B, global annual mean contrail RF for 2019 was estimated to be 62.1 mW $m^2$.[44] This study, however, also identified significant regional variation in contrail RF. In Europe and the United States, net RF was found to be 876 mW $m^{-2}$ (14 times the global average) and 414 mW $m^{-2}$ (6.6 times the global average), respectively. Taking these findings into account, applying global average RF values is clearly not appropriate when assessing the climate impact of individual flights.[45] Therefore, a methodology for baselining contrail impact should be dynamic and adaptable over time as improvements in contrail prediction modeling are made and the climate impact of contrails is better understood.

### 3.1.3. Further areas of research needed to reduce climate impact uncertainty

Research to clearly define the climate impact of contrails continues to advance; however, additional research is required. Pointing to two key areas for further inquiry, a 2023 study found that humidity and aircraft engine particle emissions have the most influence on RF estimates.[46]

In terms of humidity research, it is well understood that it is very difficult to accurately measure humidity in the upper atmosphere. Obtaining accurate real-time humidity measurements at altitude is a significant challenge to better understanding and addressing the climate impact of contrails. The development of new sensors that can be installed onto existing aircraft for the collection of additional accurate real-time data is a key action needed to improve contrail prediction. This topic is explored in section 3.2.3.

In terms of particle emissions research, in 2021, the ERF from aviation aerosol-cloud interactions for soot and sulfate remained undetermined.[47] More recently, these interactions have been noted as being a significant contributor to the high uncertainty associated with the climate impact of contrails.[48]

However, research conducted by DLR and NASA into the effects of cleaner-burning fuels on contrail formation provided experimental evidence that meaningful reductions in aviation's climate impact could be achieved through scaled adoption of low-aromatic fuels.[49] Measuring the exhaust characteristics of an Airbus A320 burning standard jet fuel and low-aromatic SAF, the research demonstrated that soot and ice concentrations were 25%–70% lower from burning low-aromatic SAF.[50] The study also noted that reduced contrail ice numbers resulted in less energy deposition and less warming. Further evidence in the effect of low-aromatic fuels on soot particle reduction and contrail ice crystal reduction was measured when following an Airbus A350 burning 100% SAF.[51] Related climate model simulations suggest a significant decrease in RF from contrails.[52] To support these findings, additional research and measurable testing to quantify the impact of low-aromatic fuels on particle emissions and associated contrail formation should be considered to better understand the effectiveness of potential contrail management solution alternatives.

## 3.2. Improving contrail prediction models

### 3.2.1. Further areas of research needed to reduce prediction modeling uncertainty

The accuracy of contrail prediction models is a subject of ongoing research and debate. Enhancing the certainty of these models requires addressing several complex questions and challenges.

One fundamental question is how to define the success of contrail prediction models. Should the focus be on predicting individual contrails, broader contrail outbreaks, or EF values? This distinction is crucial because it influences how models are evaluated and improved. Allocating a contrail to a specific flight can be challenging and compounds the problem if the objective is to trace a climate impact to a specific flight.

Another critical issue in flight planning is the definition of ISSRs and their boundaries. Should models rely solely on the Schmidt-Appleman criterion and remain aircraft agnostic, or should more complex models be integrated into flight planning? Ultimately, different aircraft flying through a similar atmosphere may trigger different contrails and boundary definitions. This illustrates the necessary trade-offs between scalability and accuracy that flight planners are facing.

Determining the source of truth for contrail-induced warming is also under debate. Should satellite observations or multiband observations of moving clouds be considered the most accurate? If yes, developments should focus on the sensor side to bridge this gap. Establishing a reliable historical ground truth of contrail geometrical parameters (e.g., thickness, crystal types, length, lifetime) is essential for validating and improving prediction models.

Several approaches are being developed, using models mentioned in chapter 2. A recent trial by American Airlines, Google Research, and Breakthrough Energy, used satellite detection to verify whether a predicted contrail was created or not (see Exhibit 9).[53] Flying one way, the flights did not adjust their trajectory to avoid contrails (the "control" group in Exhibit 9), and flying the other way, contrail avoidance was applied (the "treatment" group). The result was that the length of the contrails created were reduced by 54% when using the prediction model.

This outcome aligns with findings from other studies.[54] These results provide a reasonable starting point for further improvements.

## Exhibit 9 Contrail Prediction Model Accuracy Example

Number of flights with GOES-16 detected and undetected contrails, total detected contrail length, and total flight distance for the control and treatment groups.

| | Number of flights with no detectable contrail created | Number of flights with detectable contrail created | Sum of contrail km | Sum of total flight km |
|---|---|---|---|---|
| **Control** | 11 | 11 | 726 | 36,802 |
| **Treatment** | 18 | 4 | 321 | 35,729 |

*Flights in the control did not adjust their trajectory to avoid contrails; flights in the treatment group were adjusted to avoid contrails.*

Source: Contrail Avoidance in practice

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Numerous research areas are critical for reducing prediction model uncertainties:

1. Ice Nucleation Sources: More research is needed into microphysical processes, including ice nucleation sources.
2. Cloud-to-Cloud Interactions: Understanding interactions between clouds is crucial for accurate predictions.
3. Computational Fluid Dynamics and NWP: Enhancements in these areas can significantly improve model accuracy.
4. Flight Attribution Models: Improved models for attributing contrails to specific flights can enhance prediction accuracy.
5. Comparative Studies: More studies comparing prediction models with observations are necessary to identify deficiencies.
6. Satellite Data Coverage: The deployment of new satellites (e.g., MTG-3, EarthCARE) and better synthesis of low Earth orbit satellites can improve data quality.
7. Advanced Weather Models: Enhanced weather models (e.g., Deutscher Wetterdienst Icosahedral Nonhydrostatic (ICON), Météo-France WIMCOT and Action de Recherche Petite Echelle Grande Echelle (ARPEGE), Environment Canada High Resolution Deterministic Prediction System (HRDPS) are expected to contribute to better predictions. Additionally, improved humidity schemes, specifically two-moment schemes, are expected to enhance model precision.

Even with these improvements, contrail prediction will always involve some degree of uncertainty due to the inherent variability of meteorological phenomena, particularly in supersaturation states. Identifying small domains with a high probability of significant climate impact and demonstrating effective predictions in these areas can be a starting point.

It remains important to evaluate model accuracy based on the ability to predict contrail formation. At a time when many models are being developed and CoCiP is a fully parametric model, the number of input variables should not be considered a proxy for a model's accuracy but rather a means of flexibility to be improved.

### 3.2.2. Contrail Validation — Improving the Prediction Models

For the industry to build confidence in the ability to predict contrail formation, thorough validation investigations need to be documented and available to the wider community. This validation is key to establishing a single source of truth on contrail formation that aviation can use to judge the effectiveness of mitigation actions. The validation of contrail formation and EF estimates clearly shows room for improvement. The future of contrail validation will likely be a hybrid of observations and improved in-situ measurement sources, with each observation further boosting the confidence that an avoidance strategy is successful (see Exhibit 10).

It is worth noting that this validation effort should affect both the model input sources (engine soot emissions parameters, humidity) and contrail model outputs (contrail formation yes/no, lifetime, length, and span).

Validating contrail formation requires observing it with a sensor pointed at the cloud. To fully characterize the warming impact of a contrail, one must detect its formation; follow the contrail through its lifetime as it persists, spreads, and moves; and measure the RF imbalance in all parts of the cloud until its disappearance. The precise location of the cloud also needs to be determined. Such validation has proven incredibly difficult, and many efforts are ongoing to tackle this problem using various observation sources.

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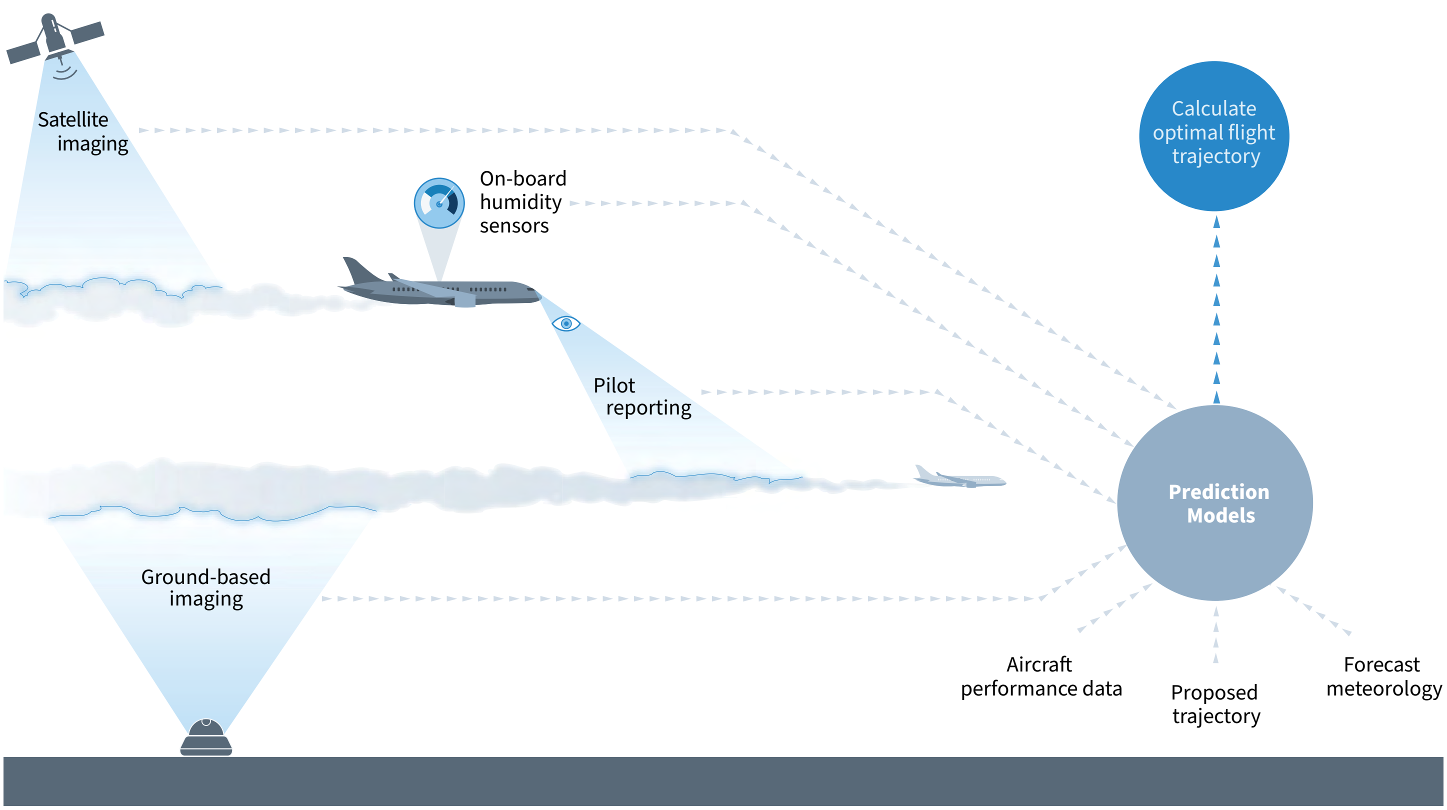
## Exhibit 10 Validation Techniques and Input Data for Contrail Prediction Modeling




RMI Graphic. Source: RMI analysis

### Ground-based observations

The first contrail model validation effort was based on ground cameras at Oberpfaffenhofen airport in Germany,[55] where the DLR has offices. The difficulty remains in following a contrail throughout its lifetime, which a fixed camera cannot do in most cases because the contrail is moving.

Some organizations are leveraging the ability to gather, label, and store larger quantities of data to start to build image repositories:

- ContrailNET is an initiative launched by Eurocontrol,[56] which is the entity in charge of coordinating ATM over Europe. Several companies have rallied the initiative, including Miratlas, a startup deploying a network of sky observing sensors, initially for space communication quality purposes.
- Breakthrough Energy launched a mobile application called the Contrail Observer so individuals spotting contrails can take pictures of them and make them available to researchers.[57]
- A network of meteor-spotting cameras maintained by NASA called CAMS could also be leveraged.[58]

Connecting large numbers of labeled images and their metadata (location, orientation, time) into a single repository is an increasingly important pursuit for and by the scientific community. A major hardship remains that most of the ground-based sensors work in the visible range of light, which could bias any validation data set toward daylight observations only.

### Satellite-based observations and machine learning

Several scientific investigations aim to establish a contrail presence baseline using satellite images. Geostationary Earth observation satellites such as GOES in the United States and EUMETSAT over Europe provide near real-time coverage but only display a resolution of several hundred meters. This resolution is too low to accurately detect a contrail at its inception. However, it is enough to spot long-lived contrails that still display a line shape before they eventually come to look like natural cirrus clouds — the type most likely to result in the biggest EF.

Other satellite technologies, such as global positioning system (GPS) radio occultation, can be leveraged. The refraction of GPS signals on atmospheric cloud layers is used to locate contrail clouds precisely. Companies using constellations of low Earth orbit satellites are developing this capability.

### In-flight observations

Some airline initiatives have used in-flight reports from pilots to help validate contrail prediction models. For instance, using a physics-based model developed by Météo France to forecast contrail formation areas, Air France established the COntrail Observation Program (COOP) to validate modeled persistent contrail areas using an in-flight reporting application.[59] This program has made thousands of observations to date. Virgin Atlantic Flight100 tested a similar in-flight contrail observation system in collaboration with RMI during the world's first transatlantic flight powered by 100% SAF operated by a commercial carrier, on November 28, 2023. Using an electronic form developed by Virgin Atlantic Flight Operations, pilots can now report contrails produced by other flights in forecast ISSRs to support contrail prediction model validation.[60]

### 3.2.3. The state of humidity sensors and opportunities for improvement

Instead of fully characterizing the three-dimensional evolution and EF of a contrail, a pragmatic first step could also be just to validate the location of ISSRs. One way for pilots to know whether they are flying in an ISSR is to equip the aircraft with humidity sensors. To date, no available humidity sensors have been specifically developed for the detection of ISSR conditions.

Humidity data is critical for accurately forecasting persistent contrail formation areas by tools such as CoCiP and others described above. To increase confidence in the effectiveness of prediction models, additional and more accurate input data is required. Current sources of humidity data used for weather modeling include scattered weather balloons, satellite data, and a limited number of civil and research aircraft equipped with sensor suites.[61] Improving humidity data quality is therefore a critical component in the effort to address the climate impact of contrails.

The In-service Aircraft for a Global Observing System (IAGOS) program currently has 10 aircraft equipped with atmospheric sensors.[62] The data collected as part of this program so far has been instrumental in recalibrating humidity values predicted by NWP models. Although most humidity sensors are quite light, the IAGOS experimental sensors are weigh up to 140 kilogram (kg) of payload on the aircraft, with the data processing unit connected to several sensors, including humidity, temperature, ozone, $NO_x$, and aerosols, among others. In time, a humidity sensor with a processing unit is expected to come down to a total weight of a few kilograms, making it more acceptable to operators.

A variety of sensors are currently available, but each has its limitations, as shown in Exhibit 11.[63] For example, even the WVSS-II sensor — one of the most capable and commercially available sensors offered by Flyht — has limited capabilities at temperatures below -50°C typically seen at cruising altitudes and difficulty measuring low water concentrations around 20 parts per million by volume (ppmv).

## Exhibit 11 **Currently Available Humidity Sensor Capabilities Compared with an Ideal Sensor**

| | Low temps -50°C or less | Low $H_2O$ concentration ~20 ppmv | High $H_2O$ concentration ~10,000 ppmv | Fast reaction time ~30-60 sec | High resolution ~7-13 km | Low maintenance | Minimum calibration | Light-weight | Easy to install |
|---|---|---|---|---|---|---|---|---|---|
| "Ideal" sensor | Green | Green | Green | Green | Green | Green | Green | Green | Green |
| ICH | Yellow | Green | Green | Yellow | Yellow | Green | Green | Green | Green |
| WVSS-II | Red | Red | Green | Green | Green | Green | Green | Green | Green |
| TAMDAR | Red | Red | Yellow | Yellow | Red | Yellow | Red | Green | Yellow |
| Chilled Mirror | Green | Green | Yellow | Red | Red | Red | Yellow | Green | Yellow |
| DLH | Yellow | Yellow | Green | Green | Green | Yellow | Yellow | Red | Red |
| FISH | Green | Green | Red | Green | Green | Red | Red | Red | Red |
| AIMS H20 | Green | Green | Red | Green | Green | Yellow | Yellow | Red | Red |
| SHARC II | Yellow | Yellow | Green | Green | Green | Green | Green | Green | Yellow |
| HAI | Yellow | Yellow | Green | Green | Green | Yellow | Green | Red | Red |

*Blue text: Installed on commercial aircraft*
*Black text: Experimental sensors on research aircraft*
*Color scale is a qualitative comparison against the ideal case*

Source: IATA

Efforts are currently underway to advance humidity sensor technology. With support from the Advanced Research Projects Agency-Energy (ARPA-E) Predictive Real-Time Emissions Technologies Reducing Aircraft Induced Lines in the Sky (PRE-TRAILS) research program, Boeing is working to develop state-of-the-art onboard humidity sensors that meet upper tropospheric requirements, require little maintenance, and remain cost-effective to enable market adoption by commercial carriers. This will support Boeing's development of a comprehensive approach for mitigating contrails which will also leverage the use of satellite observations, deep learning, and numerical weather predication modeling. The PRE-TRAILS program is also supporting Northrop Grumman in the company's efforts to develop an airborne sensor for the use of remotely measuring temperature and humidity. The ARPA-E program will be completed by the fourth quarter of 2025.[64]

However, before equipping more aircraft with humidity sensors, some challenges remain:

- The need for frequent recalibration, depending on the type of sensor used
- The lack of financial incentive to install sensors or financial incentive to avoid flying through ISSRs

# 4. Deciding When to Avoid Contrails – the Importance of Metrics

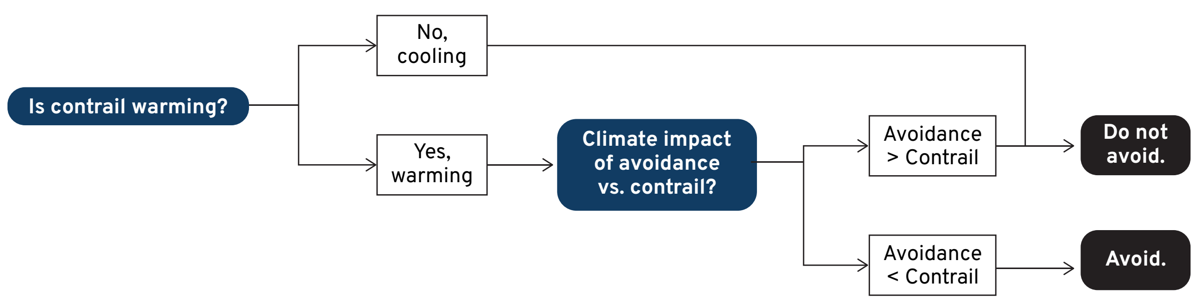
This chapter is derived from work by authors of **"Climate equivalence metrics for airline contrail mitigation"**.

How the world mitigates climate change increasingly depends on the choice of how we *measure* climate impacts. While we might prefer to simply reduce all climate change-inducing activities to a single, common metric, such as GWP, doing so would obscure important trade-offs between mitigation options. Although GWP100 is a well-established unit for GHG accounting and other international contexts, it is worth examining how other options can influence important decisions, such as whether to divert airplane flights to avoid contrail formation. Informing these decisions requires understanding the circumstances under which the choice of the climate metric changes the choice of mitigation activities.

## 4.1. Metrics' key role in contrail avoidance decision-making

Mitigating the climate impacts of aviation requires creating a decision rule for whether to avoid creating contrails. Some flights can avoid creating contrails by changing their path, but that choice typically comes at the expense of additional fuel burn and associated combustion emissions. Airline operators require rules for guiding flight-by-flight solutions to this dilemma, informed by carefully selected climate metrics. The basic decision tree in Exhibit 12 illustrates the situation. If the contrail is cooling, then it should not be avoided. If it is warming, then the decisionmaker needs to compare the climate impact of the additional fuel burn versus the climate impact of the contrail. Such a comparison requires a consistent climate equivalency metric.

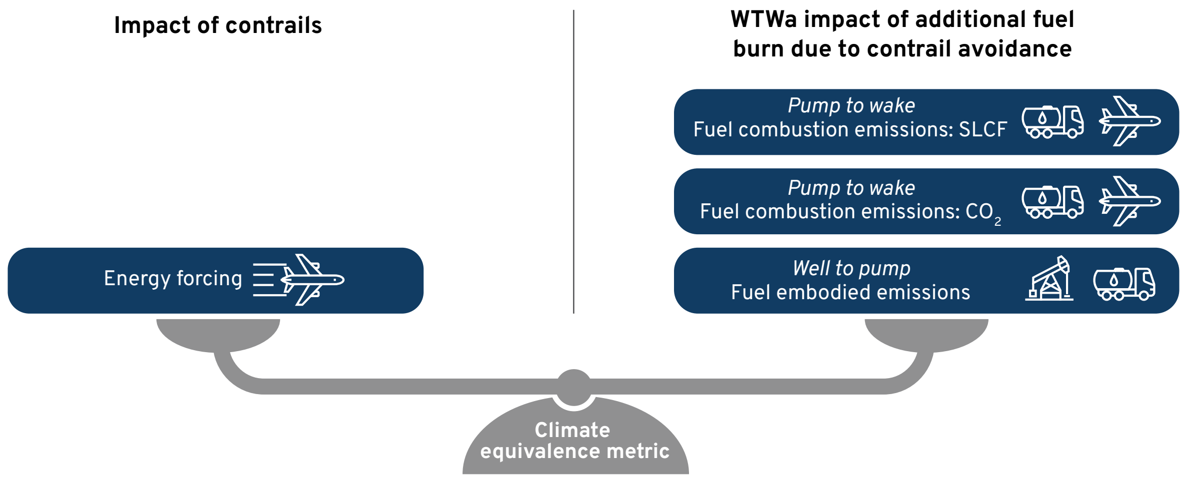
Exhibit 12 **Contrail Avoidance Decision Tree**




Source: **Climate equivalence metrics for airline contrail mitigation**

It is important to take a WTWa approach (see Exhibit 13), capturing the embodied impacts of additional fuel production, i.e., well-to-pump (WTP) due to contrail avoidance and the additional combustion-related impacts and pump-to-wake (PTWa). *If this phase is ignored, the impact of contrail avoidance will be underestimated.* For aviation-relevant short-lived climate forcers (SLCF) i.e., carbon monoxide, $NO_x$, black carbon, organic aerosols, and non-methane volatile organic compounds), the climate impacts differ if emissions take place on Earth's surface during fuel production activities versus in the troposphere during flight. Therefore, standard climate equivalence factors should be applied to these WTP fuel production emissions, and factors derived from aviation climate models should be applied to PTWa combustion emissions.[65]

## Exhibit 13 Applying Climate Equivalence Metrics to Determine the Balance Between the Impact of Contrails and the WTWa Impact of Additional Fuel Burn Due to Contrail Avoidance




Source: Climate equivalence metrics for airline contrail mitigation

This chapter surveys the options for climate metrics and suggests criteria for choosing among them. Different studies on contrails use different metrics and this lack of consensus complicates the assessment of $CO_2$ and non-$CO_2$ impact.[66] The approach in this chapter echoes previous studies on the impact of metric design on assessments of comparing natural gas and alternative shipping fuels.[67] These studies focused on methane and showed that the value of alternative technologies varied substantially depending on the climate metric used to assess them.

A 2024 study explored the implications of this metric choice through a simulation of 2019 North Atlantic air traffic, assuming a 1% increase in $CO_2$ emissions to avoid contrail formation.[68] **The researchers found that "disagreements between $CO_2$-equivalence metrics happen for about 10% of flights, which form low energy contrails that do not contribute much to climate damage anyway."**

## 4.2. Metrics for measuring the climate impact of contrails

A climate equivalency metric functions similarly to an exchange rate between two currencies. If someone received payments of US$100 and 300 renminbi, the total worth of those payments, requires first convert to a common currency. An exchange rate provides a ratio between two units of currency, showing the value of one currency in terms of another.

Likewise, for a chosen time horizon, a climate equivalency metric considers the ratio between the absolute climate impact of a given climate forcer and the absolute climate impact of 1 kg of $CO_2$ emissions. By definition, the factor for $CO_2$ is always 1 kg $CO_2$e/kg $CO_2$ regardless of metric or time horizon; the conversion factors vary for all other climate forcers. For instance, according to the latest estimates from the IPCC, the climate impact of emitting 1 kg of $N_2O$ is equivalent to emitting 273 kg $CO_2$ using the GWP100 metric, and thus its impact would be written as 273 kg $CO_2$e.

As shown in the example equations below, the GWP100 value is found by taking the ratio between the absolute global warming potential (AGWP100) of $N_2O$ and $CO_2$, and the global temperature potential (GTP100) is calculated similarly. A sum of the total climate impact of an activity can be taken once the impact of all climate forcers are converted into common units of kg$CO_2$e. The 2024 study by Borella and others used AGWP100 and absolute global temperature potential (AGTP100) directly, rather than making a comparison with $CO_2$.[69]

$$GWP100_{N_2O} = \frac{AGWP100_{N_2O}}{AGWP100_{CO_2}} = \frac{24.5\ pW\ m^{-2}\ y\ kg^{-1}_{N_2O}}{0.0895\ pW\ m\text{-}2\ y\ kg^{-1}_{CO_2}} \approx 273\ \frac{kg_{CO_2e}}{kg_{N_2O}}$$

$$GTP100_{N_2O} = \frac{AGTP100_{N_2O}}{AGTP100_{CO_2}} = \frac{0.0919\ pK\ kg^{-1}_{N_2O}}{0.000395\ pK\ kg^{-1}_{CO_2}} \approx 233\ \frac{kg_{CO_2e}}{kg_{N_2O}}$$

While GWP100 is the most common metric, there are a variety of different climate equivalency metrics, each with a different approach to expressing the impact of an emission in $CO_2$-e terms.[70] These metrics estimate various impacts, such as EF, temperature change, precipitation, sea-level rise, or even economic damage caused by a climate forcer.

In this chapter, we focus on metrics that deal with EF and temperature change, shown in Exhibit 14.

**Impact Measure:** As discussed in *Appendix A: Understanding Radiative Forcing*, RF measures the energy imbalance between preindustrial times and a given year. RF at a target year is directly captured in the instantaneous climate impact (ICI) metric. The metrics GWP, Global Warming Potential* (GWP*), and cumulative climate impact (CCI) go one step further by integrating the RF over the time horizon. GTP and ATR measure the temperature impacts of emissions, instead of the total forcing, since *temperature* is the main driver of climatic impact and also mentioned in international treaties.

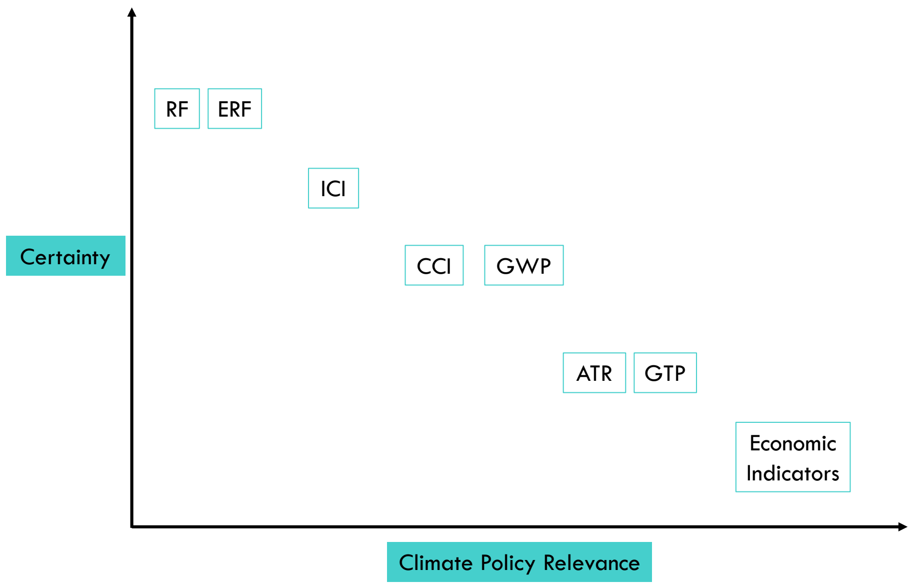
## Exhibit 14 Key Attributes of Climate Equivalency Metrics

| Impact Measure | Time Horizon | Metric | Aggregration Method | Emissions Type |
|---|---|---|---|---|
| **Radiative Forcing** (more certain, less relevant) | Static | **GWP** Global Warming Potential | Integrated over time | Pulse |
| | | **GWP*** Global Warming Potential* | Integrated over time | Step-pulse |
| | Dynamic | **CCI** Cumulative Climate Impact | Integrated over time | Pulse |
| | | **ICI** Instantaneous Climate Impact | Endpoint | Pulse |
| **Temperature** (less certain, more relevant) | Static | **GTP** Global Temperature Potential | Endpoint | Pulse |
| | | **ATR** Average Temperature Response | Average over time | Pulse |

Source: Climate equivalence metrics for airline contrail mitigation

When considering which metric to use, it is important to recognize that each was designed with a specific goal in mind, often to be relevant to policy. As illustrated in Exhibit 15, with every step toward policy relevance, a new climate metric inherits the uncertainty of the simpler model it is built upon, but also adds additional modeling assumptions, which are necessary to account for a wider range of impact mechanisms. ERF adjusts RF by making assumptions about feedback mechanisms from cloud cover changes. GTP models other feedback effects that predict temperature changes. Small adjustments in poorly understood modeling parameters can have large effects on the final estimates in complex models. With every additional climate mechanism modeled, estimates become more dependent on sensitive parameters that can have outsized effects on the range of possible results. RF or ERF at the time of flight are not considered plausible metrics because they reflect a snapshot in time and do not consider impacts over time.

## Exhibit 15 Trade-Off Between Certainty and Relevance across Climate Equivalency Metrics




Source: Climate equivalence metrics for airline contrail mitigation

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**Static Versus Dynamic Time Horizon:** Dynamic metrics differ from static metrics in that users must choose a target stabilization year, not a fixed time horizon. As the target year approaches, the time horizon used in the climate metric calculation shrinks. Dynamic metrics are therefore explicitly designed to avoid overshooting climate targets. Forthe illustrative dynamic time horizons depicted in Exhibit 16, if the target year is 2050, a pulse emission in 2025 will be evaluated over a 25-year time horizon. But an emission in 2040 will be evaluated over a 10-year horizon. By contrast, the example static time horizon of 100 years means that the climate impacts of an emission will be evaluated for the following 100 years, regardless of earlier climate targets.

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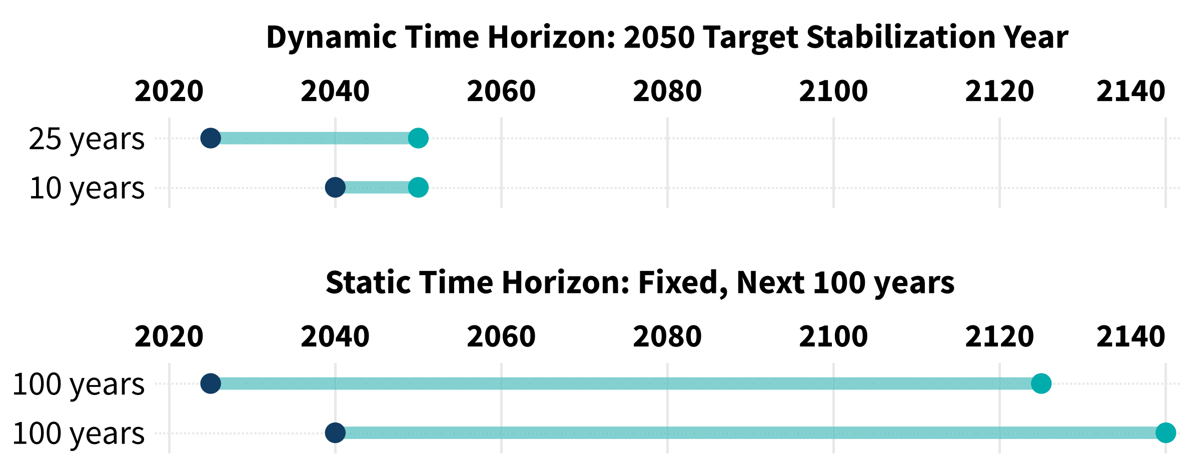
## Exhibit 16 Illustrative Dynamic and Static Time Horizons




Source: Climate equivalence metrics for airline contrail mitigation

**Aggregation Method:** Some methods take an integral of the impact over the entire time horizon, while endpoint metrics only consider the impact at the end of the time horizon. An average metric takes the average annual value across the time horizon.

**Emission Type:** Models can also differ by whether they are using pulses or steps as their basic unit of emissions. Most metrics model the effect of pulse emissions, meaning the effect of a one-off release of a gas, measured by mass. For example, the combustion emissions from a single flight are considered pulse emissions, often measured in kilograms of GHGs.. By contrast, a few metrics also incorporate steps, which are changes in emission rates of a gas, measured in mass per unit of time. For example, one could measure the change in the amount of methane emitted by agriculture from one year to the next. Steps are primarily used to estimate the effects of SLCF, as emission rates could potentially be informative about the resulting stock of the forcer affecting the climate. A brief discussion of why step-pulse metrics (i.e., GWP*) have been excluded for the purpose of estimating contrail impacts follows in *Appendix B: Pros and Cons for Different Operational Decision Metrics*.

## 4.3. Pros and cons of different operational decision metrics

Exhibit 17 summarizes the advantages and disadvantages of the various climate equivalency metrics. (For a more detailed discussion see *Appendix B)*.

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Exhibit 17 **Summary of Climate Equivalency Metrics**

| Impact Measure | Time Horizon | Metric | Pros | Cons |
|---|---|---|---|---|
| **Radiative Forcing** (more certain, less relevant) | Static | **GWP** Global Warming Potential | • Simple, widespread use | • Not temperature change<br>• Poor for short-lived forces |
| | | **GWP*** Global Warming Potential* | • Step-pulse | • Shortcomings for contrail cirrus calculations |
| | Dynamic (adjusts to target year) | **CCI** Cumulative Climate Impact | • Changes as target year nears, prevents overshoot | • (Same issues with GWP) |
| | | **ICI** Instantaneous Climate Impact | • Focuses on target year | • (Same issues with GWP) |
| **Temperature** (less certain, more relevant) | Static | **GTP** Global Temperature Potential | • Temperature change during target year, helps with targets | • Complex model, sensitive assumptions |
| | | **ATR** Average Temperature Response | • Averages the temperature change over time | • Less helpful for meeting temperature targets |

Source: Climate equivalence metrics for airline contrail mitigation

## 4.4. The importance of time horizon

Climate equivalency metrics also differ in their choice of the time horizon considered. Some metrics measure impacts that take place across time, and others simply observe the climate impact at the end of the time period. As with the broader project of combating climate change, the aviation sector is attentive to trade-offs between short- and long-term strategies. GHG emissions and contrails contrast in two major regards: duration and ease of mitigation. Some GHG emissions remain in the atmosphere for millennia, others only for a few hours. Some contrails dissipate rapidly, whereas others persist for hours or days. Even so, the climate impact from contrails can last decades through their impacts on the ocean response and the carbon feedback cycle.[71] Some GHG emissions are evenly distributed throughout the atmosphere, while contrails and other GHG emissions do not travel far from their point of emission. While contrails have many contrasts with GHGs, their impacts are still meaningful to climate change.

Despite decades of work and debate, there is no single agreed-upon time horizon for determining climate metrics. While GWP100 has been the only relevant climate metric in international treaties and climate accounting frameworks, its prevalence is historical happenstance. An influential IPCC report in 1990 proposed GWPs with 20-, 100-, and 500-year time horizons, emphasizing that these time frames were chosen arbitrarily and that future discussion needed to give the choice of time horizon more careful consideration.[72] The 1997 Kyoto Protocol used GWP100, but this choice may not have been based on careful consideration but rather a compromise because it constituted the middle value of the three time horizons proposed in 1990.[73]

The choice of time horizon can be more influential on decision-making than the choice of climate impact because the former dictates the relative weight of SLCFs to $CO_2$. Many non-$CO_2$ gasses have a climate impact (i.e., radiative efficiency) much stronger than that of $CO_2$. But while $CO_2$ can persist in the atmosphere for hundreds if not thousands of years, continuing to impact the climate throughout, most non-$CO_2$ gasses dissipate on a much shorter timeline, after which they do not impact the climate. Therefore, a short time horizon such as 20 years will tend to assign a stronger weight to short-lived GHG emissions since these SLCF will not play as important a role when using a 100-year time scale. This is true both for integrated metrics, which look at the impact over the entire time, and endpoint metrics, which only assess the impact at the end of the chosen horizon. The 2024 study by Borella and others confirmed previously observed behavior that “Time-integrated metrics defined on a short time horizon, like AGWP20 or ATR20, put more weight on contrail cirrus, while endpoint metrics on a long time horizon, like AGTP100, put more weight on $CO_2$.”[74]

The scientific community has so far proposed two methods to determine which time horizon to choose. One approach is rooted in physics, the other in economics.

### 4.4.1. Physics approach for determining time horizons

The physical approach uses climate targets as the basis for calculating appropriate time horizons. A 2022 study, for example, calculated the time horizons corresponding to the temperature targets in the Paris Climate Agreement.[75] The researchers used the current level of emissions to predict the years in which the planet will reach 1.5°C and 2°C above baseline, 2045 and 2079, respectively. The appropriate time horizon for each target was then calculated by subtracting the present year from the target years. In 2024, this corresponds to time horizons of 21 years for 1.5°C and 55 years for 2°C. Note that in this framework, time horizons shrink as the target year approaches. While this shrinkage presents no difficulty to the calculation of climate metrics, it should remind us that even the choice of a static time horizon versus a dynamic one should be informed by goals and needs.

### 4.4.2. Economic approach for determining time horizons

The economic approach bases time horizons on discount rates. Discount rates are an important tool in economics that help express the future values of benefits or costs in present values. Economic theory proposes that people place greater importance on present values than future values, and discount rates express the degree of this preference. The economic approach models the economic damages from a GHG emission and then uses the forecasted damages to calculate the discount rate implied by a given time horizon. This approach can also calculate the time horizon corresponding to a predetermined discount rate. Common discount rates, such as those used by the US government, are 3% and 7%, which researchers have estimated to imply time horizons of 118 years and 38 years, respectively.[76] An in-depth discussion of appropriate choices for discount rates is fraught with normative assumptions, and so is beyond the scope of this chapter.

## 4.5. Selection of climate impact metrics

Given the prominence of GWP100 in corporate accounting and international treaties, it seems to be inescapable for the purposes of airlines' external climate impact accounting. For operational decisions regarding whether to avoid contrail creation, it is important to adopt a climate equivalency metric and time horizon that satisfy predetermined criteria because there are situations in which the choice of metric will influence the avoidance decision. The conclusions of the 2024 study by Borella and others offer a more detailed discussion of the potential implications of selecting the various metrics in their simulation of the North Atlantic.[77] Summarizing their conclusions in this chapter, the criteria for a climate metric should consider preferences for the interrelated concepts:

- Certainty (RF-based) versus climate policy relevance (temperature-based)
- Impacts across the time horizon (integrated and average) versus at the end of the time horizon (endpoint)
- Static time horizon of 20, 50, 100, or 500 years or dynamic time horizon that adjusts as the selected target year approaches

For time horizon H, the GWP of contrails can be estimated with the following formula:[78]

$$\frac{Contrail_{GWP,H}\,[kg\ CO_2e]}{Contrail_{EF}[J]} = \frac{\frac{ERF}{RF}}{times\ per\ year[s]\ x\ Earth's\ surface\ [m^2]\ x\ AGWP_{H,CO_2}[\frac{Wm^{-2}}{kgCO_2}]}$$

Climate scientists must overcome the current challenge of constructing an efficient means for accurately converting contrail EF into temperature-based metrics (GTP and ATR), since it is impractical to run so frequently a climate model to derive these results for daily operations.

Given the scale of the industry and the importance of this decision on the climate system, global stakeholders who are especially vulnerable to the impacts of climate change should have a voice in the determination of the metric, but such consultation should not forestall action. Borella and team similarly conclude that the "lack of consensus on what is a suitable or the correct $CO_2$-equivalence metric is therefore not an obstacle to implementing contrail avoidance policies."[79]

## 4.6. Contrail decision matrix

The importance of the choice of climate metric for operational decision-making is most pronounced for low-energy contrails; however, the decision to avoid high-energy contrails is clear using most of the climate metrics discussed. To aid the operational decision-making process, the report authors created a spreadsheet showing a matrix of the impacts of contrail EF along the vertical axis, and additional fuel burn due to contrail avoidance along the horizontal axis. The values along the vertical axis are based on the estimated 2019 percentiles of EF, and are grouped into a new concept — the contrail severity index — which categorizes warming EF into groups of low, medium, and high.[80] The percentages of additional fuel-burn values along the horizontal axis grow in increments (e.g., 0.1%, 0.5%, 1%, 5%) through an extreme of 100% (doubling the fuel burn).

In the spreadsheet, one selects first the GWP time horizon and the GREET1 2023 aircraft type used to approximate the default fuel burn (kg fuel/km flight distance).[81] The matrix is currently available for GWP20 and GWP100, but future efforts could develop it for more climate equivalency metrics. The default values of four variables can be overridden with custom inputs:

- Ratio between contrail ERF/RF, default: 0.42[82]
- Fuel burn
- WTWa impact of additional fuel burn[83]
    - 12.66 kg $CO_2$e/kg fuel for GWP20
    - 5.20 kg $CO_2$e/kg fuel for GWP100
- $AGWP_{CO_2}$,[84]
    - 2.43E-14 $Wm^{-2}y$ kg $CO_2^{-1}$ for AGWP20
    - 8.95E-14 $Wm^{-2}y$ kg $CO_2^{-1}$ for AGWP100

After making the choice above, to use the matrix, first locate the row that reflects the estimated EF per flight distance of the expected contrail from the flight. Next, locate the column that reflects the estimated additional fuel burn to avoid creating the contrail. At the intersection of that row and column, the value in the matrix provides the impact from contrails less the impact from additional fuel burn due to contrail avoidance. Therefore, positive values represent climate impact savings due to contrail avoidance; negative values indicate that it is not beneficial to avoid the contrail.

Exhibit 18 illustrates the spreadsheet estimates for two GWP time horizons and aircraft types. For both cases, cooling contrails (blue category on vertical axis) always have negative values and should not be avoided, which aligns with the decision tree in Exhibit 12. Also, in both cases the high-severity contrails have large positive savings values (darker green) and should always be avoided, regardless of additional fuel burn. In these examples, the areas where decisions must be made about diversion occur when the contrail severity is low or medium, and the additional fuel burn is high or very high. The choice of GWP time horizon and aircraft slightly change the threshold for which levels of contrail severity and additional fuel burn result in a change from positive to negative savings.

Uncertainty could be factored in by estimating a confidence interval for the EF values and the additional fuel percentage for the case of the flight at hand, and then identifying in which rectangular region of the matrix the case lies in. If there are solely positive or negative values in that region, the decision is clear. If there is a mix of positive and negative values, then ideally the data would be refined to reduce the uncertainty, thus focusing on a smaller region for decision-making.

An even more thorough approach to handling uncertainty would involve implementing a Monte Carlo simulation. This technique applies probability distributions (such as mean and standard deviation) to the baseline values of the input data, and therefore the outputs of the simulation have a probability distribution as well, rather than a single calculated value, which could lead to a false assumption of precision and accuracy. A 2023 study demonstrated the use of Monte Carlo simulations for this purpose in their comparative life-cycle assessment of hydrogen jet fuels.[85] If savings are positive, contrails should be avoided; if negative, they should not be.

## Exhibit 18 Decision Matrix for Contrail Avoidance GWP20 (Upper) and GWP100 (Lower)

**Select Time Horizon and Aircraft Type:**

| | Selections: |
|---|---|
| GWP Time Horizon: | 20 |
| GREET Aircraft: | Small Twin Aisle (STA) |

**Override default values with custom input:**

| | Contrail ERF / RF | Fuel burn (kg fuel / km) | Fuel Burn WTWa impact (kg CO2e / kg fuel) | AGWP (Wm-2 yr kg CO2-1) |
|---|---|---|---|---|
| Default: | 0.42 | 6.09 | 12.66 | 2.43E-14 |
| Custom: | | | | |
| Final: | 0.42 | 6.09 | 12.66 | 2.43E-14 |

**Impact Calculations:**

| Contrail impact (kg CO2e/J) | Fuel Burn WTWa impact (kg CO2e / km) |
|---|---|
| 1.07E-09 | 77.13 |

| Contrails | | | | Savings from Avoiding Contrails (GWP20, kg CO2e per km flight) | | | | | | | | | | Contrail Avoidance Action |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Contrail Severity | EF Percentile (Year 2019) | EF per flight distance (J/m) | Contrail Impact (kg CO2e/km) | Impact from Contrails - Impact from Additional Fuel Burn due to Contrail Avoidance | | | | | | | | | | |
| High | 99 | 3.14E+09 | 3373.7 | +3374 | +3374 | +3374 | +3374 | +3373 | +3373 | +3370 | +3366 | +3335 | +3297 | |
| | 95 | 1.63E+09 | 1751.3 | +1751 | +1751 | +1751 | +1751 | +1751 | +1751 | +1747 | +1744 | +1713 | +1674 | |
| | 90 | 1.01E+09 | 1085.2 | +1085 | +1085 | +1085 | +1085 | +1085 | +1084 | +1081 | +1077 | +1047 | +1008 | |
| | 85 | 6.72E+08 | 722.0 | +722 | +722 | +722 | +722 | +722 | +721 | +718 | +714 | +683 | +645 | If Positive (+) Savings, Avoid Contrails. |
| Medum | 80 | 4.57E+08 | 491.0 | +491 | +491 | +491 | +491 | +491 | +490 | +487 | +483 | +452 | +414 | |
| | 75 | 3.07E+08 | 329.9 | +330 | +330 | +330 | +330 | +329 | +329 | +326 | +322 | +291 | +253 | |
| | 70 | 2.00E+08 | 214.9 | +215 | +215 | +215 | +215 | +215 | +214 | +211 | +207 | +176 | +138 | |
| | 65 | 1.23E+08 | 132.2 | +132 | +132 | +132 | +132 | +132 | +131 | +128 | +124 | +94 | +55 | |
| | 60 | 7.06E+07 | 75.9 | +76 | +76 | +76 | +76 | +75 | +75 | +72 | +68 | +37 | -1 | |
| | 55 | 3.72E+07 | 40.0 | +40 | +40 | +40 | +40 | +40 | +39 | +36 | +32 | +1 | -37 | |
| Low | 50 | 1.74E+07 | 18.7 | +19 | +19 | +19 | +19 | +18 | +18 | +15 | +11 | -20 | -58 | *If Negative (-) Savings, Don't Avoid Contrails.* |
| | 45 | 6.31E+06 | 6.8 | +7 | +7 | +7 | +7 | +6 | +6 | +3 | -1 | -32 | -70 | |
| | 40 | 9.05E+05 | 1.0 | +1 | +1 | +1 | +1 | +1 | +0 | -3 | -7 | -38 | -76 | |
| Very Low | | 9.05E+02 | 0.0 | +0 | -0 | -0 | -0 | -0 | -1 | -4 | -8 | -39 | -77 | |
| Cooling | 35 | -2.74E+05 | -0.3 | -0 | -0 | -0 | -0 | -1 | -1 | -4 | -8 | -39 | -77 | |
| | 30 | -1.47E+06 | -1.6 | -2 | -2 | -2 | -2 | -2 | -2 | -5 | -9 | -40 | -79 | |
| | 25 | -2.69E+06 | -2.9 | -3 | -3 | -3 | -3 | -3 | -4 | -7 | -11 | -41 | -80 | |
| | 20 | -7.78E+06 | -8.4 | -8 | -8 | -8 | -8 | -9 | -9 | -12 | -16 | -47 | -85 | *Don't Avoid Cooling (-) Contrails.* |
| | 15 | -2.45E+07 | -26.3 | -26 | -26 | -26 | -26 | -27 | -27 | -30 | -34 | -65 | -103 | |
| | 10 | -6.93E+07 | -74.5 | -74 | -74 | -74 | -75 | -75 | -75 | -78 | -82 | -113 | -152 | |
| | 5 | -1.95E+08 | -209.5 | -210 | -210 | -210 | -210 | -210 | -210 | -213 | -217 | -248 | -287 | |
| | 1 | -6.39E+08 | -686.6 | -687 | -687 | -687 | -687 | -687 | -687 | -690 | -694 | -725 | -764 | |
| | | | Additional fuel burn impact (kg CO2e/km) | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 0.8 | 3.9 | 7.7 | 38.6 | 77.1 | |
| | | | Additional fuel burn (kg/km) | 0.0E+00 | 6.1E-04 | 3.0E-03 | 6.1E-03 | 3.0E-02 | 6.1E-02 | 3.0E-01 | 6.1E-01 | 3.0E+00 | 6.1E+00 | |
| | | | Additional fuel burn (%) | 0.00% | 0.01% | 0.05% | 0.10% | 0.50% | 1% | 5% | 10% | 50% | 100% | |
| | | | | Low | | | | | Medium | High | | Very High | | |
| | | | | Additional Fuel Burn due to Contrail Avoidance | | | | | | | | | | |

**Select Time Horizon and Aircraft Type:**

| | Selections: |
|---|---|
| GWP Time Horizon: | 100 |
| GREET Aircraft: | Large Quad (LQ) |

**Override default values with custom input:**

| | Contrail ERF / RF | Fuel burn (kg fuel / km) | Fuel Burn WTWa impact (kg CO2e / kg fuel) | AGWP (Wm-2 yr kg CO2-1) |
|---|---|---|---|---|
| Default: | 0.42 | 12.93 | 5.20 | 8.95E-14 |
| Custom: | | | | |
| Final: | 0.42 | 12.93 | 5.20 | 8.95E-14 |

**Impact Calculations:**

| Contrail impact (kg CO2e/J) | Fuel Burn WTWa impact (kg CO2e / km) |
|---|---|
| 2.92E-10 | 67.19 |

| Contrails | | | | Savings from Avoiding Contrails (GWP100, kg CO2e per km flight) | | | | | | | | | | Contrail Avoidance Action |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Contrail Severity | EF Percentile (Year 2019) | EF per flight distance (J/m) | Contrail Impact (kg CO2e/km) | Impact from Contrails - Impact from Additional Fuel Burn due to Contrail Avoidance | | | | | | | | | | |
| High | 99 | 3.14E+09 | 916.0 | +916 | +916 | +916 | +916 | +916 | +915 | +913 | +909 | +882 | +849 | |
| | 95 | 1.63E+09 | 475.5 | +476 | +475 | +475 | +475 | +475 | +475 | +472 | +469 | +442 | +408 | |
| | 90 | 1.01E+09 | 294.6 | +295 | +295 | +295 | +295 | +294 | +294 | +291 | +288 | +261 | +227 | |
| | 85 | 6.72E+08 | 196.0 | +196 | +196 | +196 | +196 | +196 | +195 | +193 | +189 | +162 | +129 | If Positive (+) Savings, Avoid Contrails. |
| Medum | 80 | 4.57E+08 | 133.3 | +133 | +133 | +133 | +133 | +133 | +133 | +130 | +127 | +100 | +66 | |
| | 75 | 3.07E+08 | 89.6 | +90 | +90 | +90 | +89 | +89 | +89 | +86 | +83 | +56 | +22 | |
| | 70 | 2.00E+08 | 58.3 | +58 | +58 | +58 | +58 | +58 | +58 | +55 | +52 | +25 | -9 | |
| | 65 | 1.23E+08 | 35.9 | +36 | +36 | +36 | +36 | +36 | +35 | +33 | +29 | +2 | -31 | |
| | 60 | 7.06E+07 | 20.6 | +21 | +21 | +21 | +21 | +20 | +20 | +17 | +14 | -13 | -47 | |
| | 55 | 3.72E+07 | 10.9 | +11 | +11 | +11 | +11 | +11 | +10 | +7 | +4 | -23 | -56 | |
| Low | 50 | 1.74E+07 | 5.1 | +5 | +5 | +5 | +5 | +5 | +4 | +2 | -2 | -29 | -62 | *If Negative (-) Savings, Don't Avoid Contrails.* |
| | 45 | 6.31E+06 | 1.8 | +2 | +2 | +2 | +2 | +2 | +1 | -2 | -5 | -32 | -65 | |
| | 40 | 9.05E+05 | 0.3 | +0 | +0 | +0 | +0 | -0 | -0 | -3 | -6 | -33 | -67 | |
| Very Low | | 9.05E+02 | 0.0 | +0 | -0 | -0 | -0 | -0 | -1 | -3 | -7 | -34 | -67 | |
| Cooling | 35 | -2.74E+05 | -0.1 | -0 | -0 | -0 | -0 | -0 | -1 | -3 | -7 | -34 | -67 | |
| | 30 | -1.47E+06 | -0.4 | -0 | -0 | -0 | -0 | -1 | -1 | -4 | -7 | -34 | -68 | |
| | 25 | -2.69E+06 | -0.8 | -1 | -1 | -1 | -1 | -1 | -1 | -4 | -8 | -34 | -68 | |
| | 20 | -7.78E+06 | -2.3 | -2 | -2 | -2 | -2 | -3 | -3 | -6 | -9 | -36 | -69 | *Don't Avoid Cooling (-) Contrails.* |
| | 15 | -2.45E+07 | -7.1 | -7 | -7 | -7 | -7 | -7 | -8 | -11 | -14 | -41 | -74 | |
| | 10 | -6.93E+07 | -20.2 | -20 | -20 | -20 | -20 | -21 | -21 | -24 | -27 | -54 | -87 | |
| | 5 | -1.95E+08 | -56.9 | -57 | -57 | -57 | -57 | -57 | -58 | -60 | -64 | -90 | -124 | |
| | 1 | -6.39E+08 | -186.4 | -186 | -186 | -186 | -186 | -187 | -187 | -190 | -193 | -220 | -254 | |
| | | | Additional fuel burn impact (kg CO2e/km) | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.7 | 3.4 | 6.7 | 33.6 | 67.2 | |
| | | | Additional fuel burn (kg/km) | 0.0E+00 | 1.3E-03 | 6.5E-03 | 1.3E-02 | 6.5E-02 | 1.3E-01 | 6.5E-01 | 1.3E+00 | 6.5E+00 | 1.3E+01 | |
| | | | Additional fuel burn (%) | 0.00% | 0.01% | 0.05% | 0.10% | 0.50% | 1% | 5% | 10% | 50% | 100% | |
| | | | | Low | | | | | Medium | High | | Very High | | |
| | | | | Additional Fuel Burn due to Contrail Avoidance | | | | | | | | | | |

Source: Climate equivalence metrics for airline contrail mitigation; https://github.com/treedmiller/contrail-climate-metrics/tree/decision-matrix

# 5. Contrail Research, Trials, and Avoidance Processes

## 5.1. The landscape of contrail avoidance trials and research

Despite uncertainty associated with the exact climate impact of contrails, it is well understood based on research to date that the impact is significant, ranging from 0.5 to 3 times the average ERF of $CO_2$.[86] The aviation industry recognizes that contrails have an overall warming effect and supports actions to address this warming as well as the need for further research to improve climate impact and contrail solution certainty as discussed above.[87] Over the past three years, the aviation industry has been hard at work conducting trials and research. Following is a sample of the activities undertaken by the aviation industry and scientific community to advance understanding of the climate impact of contrails and solutions.

- Established in 2014, the IAGOS research program collects global atmospheric data using sensors onboard active commercial aircraft. IAGOS observes pressure, temperature, and humidity data by flight, and the data is sent to weather service providers to support forecasts. As of April 2024, IAGOS instruments were installed on 10 active aircraft operated by eight airlines globally.[88]

- In 2015 and 2018, DLR and NASA collaborated on two research flight tests as part of the ECLIF project. Using DLR's Airbus A320 aircraft and NASA's DC-8, the ECLIF1 (2015) and ECLIF2/ND-MAX (2018) sampled the exhaust plume and contrail properties based on various alternative fuel blends. Overall, the flight tests produced evidence that low-aromatic SAF can reduce soot and ice particle numbers, finding that adoption of low-aromatic fuels could result in meaningful reductions in aviation's climate impact.[89]

- In 2021, EUROCONTROL's Maastricht Upper Area Control Centre (MUAC) and DLR conducted the world's first live trials on contrail prevention. Over the course of 10 months, 209 aircraft trajectories were evaluated to test the technical feasibility of contrail prevention, the accuracy of ISSR forecasts, and the operational feasibility of vertical contrail prevention at specific air traffic capacity.[90]

- In 2021, SATAVIA worked with Etihad Airways to implement contrail management for the first time on a commercially operated flight, Flight EY20 from London Heathrow to Abu Dhabi."[91]

- In 2022, Delta Air Lines and MIT's Department of Aeronautics and Astronautics began a collaboration to test contrail forecast methods and develop tools to eliminate persistent contrails.[92] Initial results indicate that reliable identification of persistent contrail regions was lacking, showing a need for improved forecast capabilities.[93]

- In 2022, Météo-France developed the WIMCOT model to forecast persistent contrail areas. In collaboration with Air France, COOP was developed to support model validation. Over a two-year period, nearly 3,000 ground and flight-based observations have been made worldwide.[94]

- In 2022, global flight planning service provider FLIGHTKEYS integrated the CoCiP model into its proprietary FLIGHTKEYS 5D flight planning service, an industry first. This integration enables pre-tactical contrail avoidance in the planning phase through vertical and horizontal deviations around forecast contrail formation areas. In addition to participating in contrail avoidance live trials, FLIGHTKEYS has simulated tens of thousands of flights to assess contrail avoidance feasibility.[95]

- In 2023, following 2015 and 2018 ECLIF flight tests, DLR, Airbus, Rolls-Royce, and Neste collaborated on ECLIF3. This project used an Airbus A350 powered by Rolls-Royce Trent XWB-84 engines operating on 100% HEFA-Synthetic Paraffinic Kerosene SAF. A 56% reduction in ice particle numbers was measured for the 100% SAF fuel in cruise conditions compared with Jet A-1. The result indicates that higher hydrogen content fuels and cleaner engines with lower particle emissions may reduce the climate impact of contrails.[96]

- In 2023, American Airlines flew 70 test flights over six months using Google's AI-based contrail prediction model and Breakthrough Energy's open-source contrail prediction model to avoid regions likely to production contrails. Analyzing satellite imagery post flight, researchers found that flights where contrail forecast areas were considered realized a 54% reduction in contrails formed as measured by distance compared with flights that did not apply contrail avoidance.[97]

- In 2023, Etihad Airways signed a multiyear agreement with SATAVIA to integrate contrail avoidance solutions with day-to-day operations.[98] SATAVIA provides contrail forecast services to its customers and calculates RF impact reduction converted to $CO_2$e. Also in 2023, with funding made available by both UK and European space agencies, SATAVIA engaged with 12 airlines over a 10-month period on 65 optimized flights using its DECISIONX software.[99]

- Boeing ecoDemonstrator ground tests with Alaska Airlines, GE, and NASA in 2021 the impact of SAF on $CO_2$ emissions and non-$CO_2$ effects — which resulted in dramatic particle emissions reductions. In 2023 Boeing, GE, NASA, and United Airlines launched a ground and flight test program to evaluate non-$CO_2$ effects from SAF and the impact on contrail formation.[100]

- On November 28, 2023, Virgin Atlantic became the first commercial airline to operate a 100% SAF powered flight on a transatlantic route, from London to New York City.[101] Flight100 also integrated contrail prediction modeling tools developed by Breakthrough Energy into flight planning operations and tested an in-flight contrail observation process developed by Virgin Atlantic to support contrail model validation.

- In 2023, under the EU's SESAR Joint Undertaking program, a group of stakeholders initiated the CICONIA project. Lead by Airbus, CICONIA is a multiyear, multistakeholder collaboration that aims to improve weather forecast capabilities, improve climate impact assessments, define and assess concepts of operation for climate impact mitigation, and demonstrate operational feasibility of minimizing strongly warming contrails. Over a three-year period, CICONIA will define the level of forecast service achievable to support operational decisions that are effective for the climate, examine the accuracy of assessing the climate impact of contrails and non-$CO_2$ effects from individual flights, choose a metric that addresses both $CO_2$ and non-$CO_2$ climate effects, and measure the efficiency of various operational mitigations options in both environmental and economic terms.[102]

- In July 2023, under the EU's SESAR Joint Undertaking program, the dynamic collaboration to generalize eco-friendly trajectories (CONCERTO) project was initiated. In a three-year effort led by THALES, the CONCERTO project is working with air navigation service providers, airlines, academic institutions, and others to develop two solutions — namely, an orchestrator for eco-friendly trajectories (focused on $CO_2$) and a traffic flow optimizer based on the total climate effect of aviation (focused on both $CO_2$ and non-$CO_2$ effects).

- In August 2023, the US Department of Energy through ARPA-E announced the allocation of $10 million dollars to support PRE-TRAILS. Five projects were selected to support research in the development of improved onboard aircraft atmospheric condition sensors, contrail prediction models, and approaches for observation and validation. Organizations selected include GE Research in collaboration with Southwest Airlines, RTX Technologies Research Center, Boeing, Universities Space Research Association, and Northrop Grumman.[103]

- In June 2024, data platform Estuaire announced an investment from Safran Ventures and a collaboration with Safran, covering end-to-end contrail management and an investigation of Sustainable Aviation Fuel deployment strategies to minimize non-$CO_2$ effects.

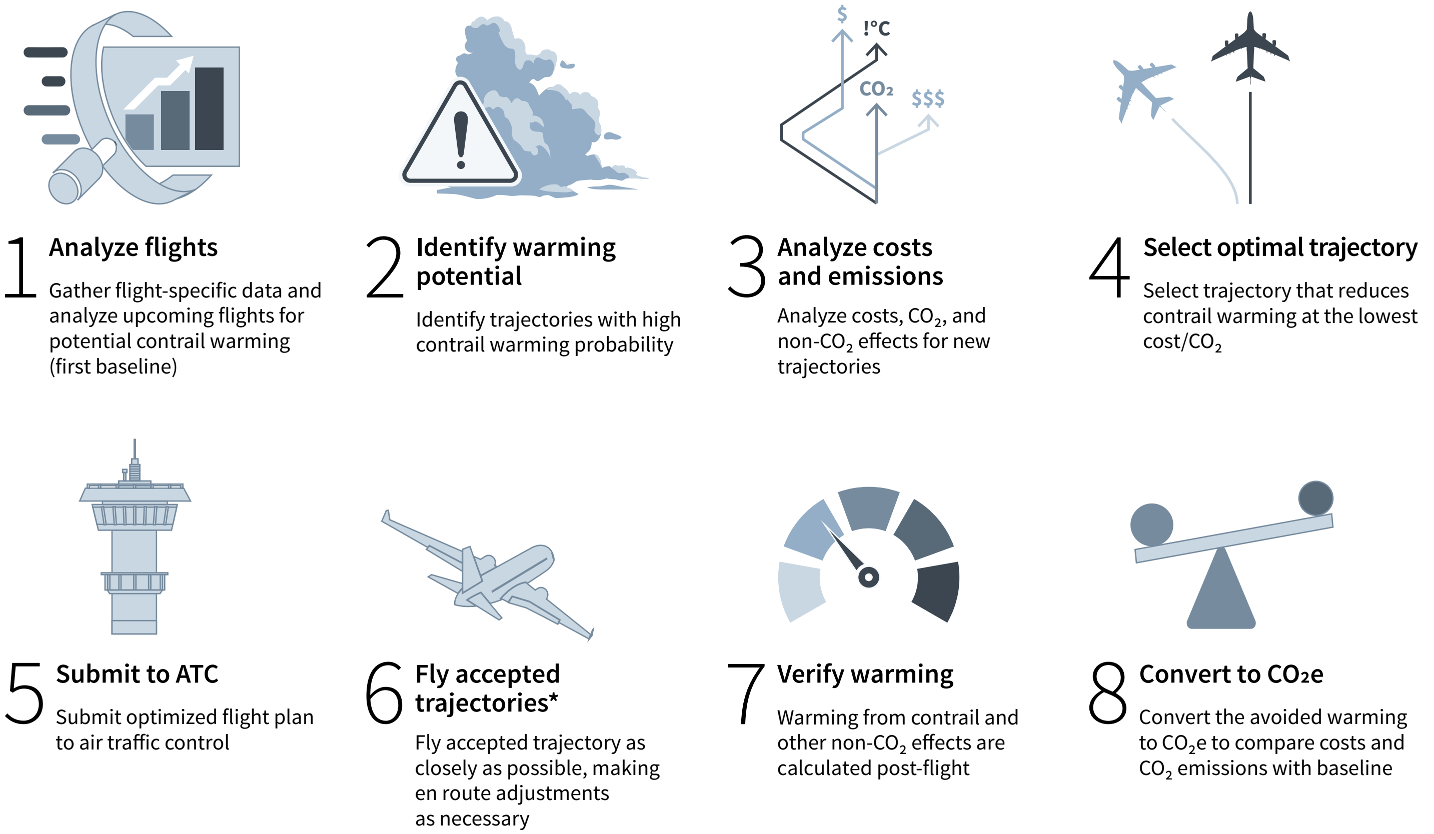
### 5.1.1. The importance of collaboration for advancing contrail science and solutions

Preliminary research and flight trials have expanded understanding of the climate impact of contrails and potential mitigation options. From rerouting aircraft, developing new sensors, and model validation approaches, to increasing the use of cleaner burning SAF, the aviation industry is working to address the non-$CO_2$ effects of aviation. Stakeholders from across the aviation value chain are collaborating to address the remaining challenges in scaling contrail management solutions — such as verification of contrail prediction modeling accuracy and the lack of standardized reporting processes for communicating the climate impact of contrails. Continued collaboration on research and technology development as well as on simulated and live trials assessing contrail avoidance strategies will be critical to advance understanding of the non-$CO_2$ effects of aviation and the industry's ability to address them.

## 5.2. Contrail avoidance process flow

Climate-optimized flight trials are still a relatively new research area; therefore, operational trials have involved extensive manual handling. This is about to change as contrail prediction models are being integrated into flight planning software.

## Exhibit 19 **Pre-tactical Trial-Based Contrail Avoidance Process Flow**




* Trajectories are regularly dynamically adjusted from the flight plan filed due to factors such as other air traffic and weather, which may limit the ability to fly a climate optimized flight plan

RMI Graphic. Source: RMI analysis

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1. Exhibit 19 is a contrail avoidance process flow diagram illustrating the processes used in recent flight-by-flight operational trials.[v] With a possible future scale-up of contrail avoidance, it is likely that the process flow will be adapted over time, especially if future contrail avoidance will be carried out at a system-wide level with ATM at the center as described in chapter 7. In most operational trials so far, the first step is to gather data about upcoming flights and use a prediction model to analyze for contrail-prone weather conditions that any aircraft might be flying through. This also determines the baseline warming against which the warming from the actual flown trajectory is compared.

2. This analysis is used to identify the few flights with high contrail-induced warming probability.

3. Cost and $CO_2$ emissions are calculated for contrail-avoiding trajectories.

4. Then, considering safety, turbulence, and system-level effects, the trajectories that reduce the most contrail-induced warming at the lowest cost and $CO_2$ emissions are selected.

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v Created with inputs from FLIGHTKEYS, SATAVIA, and other participants of the Contrail Impact Task Force.

5. The new flight plans are submitted to ATC and approved or denied.

6. Approved new flight plans are followed, with enroute adjustments if necessary.

7. Post flight, contrail-induced warming and other non-$CO_2$ effects are calculated and verified.

8. Finally, the avoided contrail-induced warming is converted to $CO_2e$ to compare costs and $CO_2e$ impact against the baseline.

## 5.3. Contrail forecasting integrated into flight planning tools

Parts of this contrail avoidance process can be automated through the flight planning tools that airlines already use to optimize for safety and cost when planning their trajectories. FLIGHTKEYS was the first flight planner to automate some of the steps in its software, offering contrail cost analysis and avoidance to its airline customers as a trial in 2023. FLIGHTKEYS software allows for pre-tactical contrail avoidance in the planning phase through cost-optimal vertical and horizontal route deviations around contrail formation regions (process flow steps 1–4). Additionally, its flight-deck assistant tablet app provides pilots with decision support on tactical contrail avoidance (step 6).

German flight planner Lido is also developing its own contrail integration to be released in 2025.[vi] In May 2024, Boeing's ForeFlight announced that it had entered a partnership with Breakthrough Energy to have its forecasting tool folded into Foreflight's planning suite.[104]

### 5.3.1. Contrail avoidance as a service

Apart from using flight planning software with contrail avoidance integration, airlines can also engage with software companies offering contrail avoidance as a service, which include Estuaire, SATAVIA, and Thales.

Typically, these companies receive upcoming flight plans from their airline customers, analyze them for non-$CO_2$ impacts, and use their proprietary software to suggest new contrail-reducing flight trajectories for the few flights with high contrail-induced warming potential. These new trajectories are then returned to the airlines for further handling. Post flight, these companies will often calculate the non-$CO_2$ warming avoided and convert it to $CO_2e$ (process flow steps 7 and 8) to inform customers how many tons of $CO_2e$ was saved by mitigating the worst warming contrails. To ensure integrity, robust methodologies should be developed for verification by certified third parties. Verification of the climate savings is critical to ensure service credibility and build trust with the industry.

## 5.4. Contrail avoidance decision-making (by flight, region, etc.)

As detailed in chapter 4, the metric used to measure the climate impact of contrails contributes significantly to the decision of whether to apply contrail avoidance on a given flight. The metric selected can have implications on the fuel-burn threshold appropriate to ensure a net climate benefit per flight. Cost thresholds must also be taken into consideration when deciding to apply contrail avoidance. Although the environmental benefit of an action taken to avoid a contrail may be clear on a given flight, the cost to do so may be economically prohibitive in the absence of financial incentives or policy measures to

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**vi** Lido presented its plans at the Canso/Eurocontrol Sustainable Skies conference, in November 2023.

support contrail avoidance. Given that the climate impact of contrails is globally disproportionate, regional mechanisms based on the impact per flight may be appropriate to maximize contrail avoidance.

## 5.5. Dispatcher and flight crew procedures, training, and operations

The application of contrail prediction models today is a relatively manual process requiring close coordination among prediction modelers, flight planning providers, and airline operations personnel. As research to better understand the climate impact of contrails and contrail avoidance flight trials advance, it is important to consider the additional training that may be required to ensure dispatchers and pilots have the resources and skills to implement contrail avoidance procedures safely and effectively.

Regardless of the level of potential automation, flight operations personnel should have a fundamental understanding of contrail avoidance. Educational programs will be needed to communicate the current understanding of the climate impact of contrails, the solutions to reduce their warming, and how important the engagement of flight operations personnel is for the success of contrail management. This may build support for developing clear procedures for relaying information used by dispatchers to consider applying contrail avoidance on a given flight, how that information will be communicated to pilots, and how contrail avoidance actions taken are monitored and reported.

## 5.6. In-flight contrail avoidance

Contrail avoidance trials today are primarily initiated through pre-tactical methods involving coordination among contrail prediction modelers, flight planners, and airline flight operations personnel. This approach places the decision to apply contrail avoidance solutions at the aircraft operator level. As an alternative, contrail avoidance may also be initiated tactically in-flight by air traffic controllers. In 2021, EUROCONTROL's MUAC, in partnership with DLR, conducted the world's first operational live contrail avoidance trial involving 209 trajectories over a 10-month period.[105] In this trial, predicted ISSRs were evaluated and instructions were then provided to air traffic controllers to avoid specific regions of airspace.

Although this trial demonstrated that in-flight tactical contrail avoidance can be done, it also identified issues that must be addressed, such as prediction model accuracy, real-time feedback processes, and appropriate air traffic controller actions in specific circumstances. Regardless of pre-tactical or tactical contrail avoidance applications, training for both ATCOs and pilots will need to be developed to ensure the safe and effective application of new procedures. For further considerations of tactical contrail avoidance, see chapter 7.

A potentially significant limitation with tactical contrail avoidance that requires further consideration is the current inability to account for potential additional $CO_2$ emissions associated with specific flights that have not initiated pre-tactical contrail avoidance strategies. This may increase the risk of contrail avoidance actions resulting in adverse climate outcomes for some flights.

# 6. Development of Contrail Climate Impact Monitoring, Reporting, and Verification Fundamentals

There is a clear need for a better understanding and a regular accounting of the contrail impact of aviation. MRV is one such framework that is used internationally and across all industries for the quantification and regulation of GHG emissions. It is a key instrument used by the United Nations Framework Convention on Climate Change and the Convention of Parties in monitoring progress of countries toward the Paris Climate Agreement.[106]

## 6.1. Monitoring, Reporting, and Verification Fundamentals

MRV provides a framework that is used to create and maintain emissions inventories of regulated entities. Existing MRV systems within the aviation sector are in place to inventory and regulate $CO_2$ emissions. The definitions and examples that follow describe frameworks that have been developed for $CO_2$ regulation. In the case of non-$CO_2$ impacts, an MRV could serve as a mechanism for data collection to improve impact estimation processes and help further scientific research. There are differences in measuring $CO_2$ emissions and estimating the warming impact of contrails. These distinctions are detailed in the following sections, where the structural components of a non-$CO_2$ MRV framework are presented.

MRV systems are in use by regulatory authorities worldwide, including the ICAO for CORSIA and the EU for its Emissions Trading System. The three steps of the MRV process — monitoring, reporting, and verification — are designed to ensure that action toward mitigation is validated by robust data and consistent requirements across the sector. These steps have well-defined roles and responsibilities for the relevant parties, exemplified below with the CORSIA MRV procedure for $CO_2$ emissions.[107]

**Monitoring** refers to the continuous process of data collection and associated calculations performed by the regulated entity to quantify the emissions from its activities. In the case of the CORSIA MRV process, the regulated entity are aircraft operators, the data collected is the fuel burn for each flight, and the associated calculation converts the fuel burn into a $CO_2$ emissions number. The complexities of estimating contrail climate impacts, which require more extensive data collection and calculations, are detailed in Section 6.2.1.

**Reporting,** typically done annually, refers to the submission of the emissions inventory by the regulated entity to the regulator and the verifier. In the case of the CORSIA MRV process, the aircraft operators must report the emissions inventories to the state authority, which in turn reports the inventories to ICAO.

**Verification** of the reported data is done by a third party (the verifier), which is typically provided all the collected data, monitoring procedures, and calculations that were performed by the regulated entity. The verifier is responsible for identifying noncompliance and any inconsistencies in the monitoring and reporting steps. In the case of the CORSIA MRV process, verification is done at three levels: first, internally by the aircraft operator; second, externally by a third-party verifier; and lastly, by the state authority.

## 6.2 Considerations for the development of an MRV framework

As mentioned earlier, there are clear differences in measuring $CO_2$ emissions and estimating the warming impact of contrails. It is important to acknowledge the uncertainties associated with estimating the climate impact of contrails from aviation. As scientific research progresses and measurement techniques improve, there will be some reduction in uncertainty. Data collected from an MRV system could contribute to this progress. However, given the complexity of the physical and chemical processes that result in contrails, it is unlikely that the non-$CO_2$ impact of aviation will ever be estimated with the same level of certainty as the $CO_2$ impact.

This necessitates certain guiding principles for the design of a robust MRV system that can help advance scientific knowledge and understanding of the climate impact of contrails while providing the ability to measure the benefits or drawbacks of contrail management techniques.

1. **An MRV framework must be robust and capable of incorporating the latest research findings into its modeling and measurement methods.** The science of contrail impact estimation has been progressing for over 20 years and continues to improve. Incorporating the best available science into the MRV process is necessary to ensure continued improvement in impact estimation and reduction in uncertainty.

2. **Monitoring plans should capture sufficiently detailed data to quantify the impact of contrails and the impact of contrail management techniques.** Methods to quantify the impact of contrails vary in their specificity. To maximize the utility and accuracy of an MRV framework, quantification methods and data collection practices need to be detailed enough to capture the impact of mitigation techniques such as avoidance maneuvers and fuel composition changes.

3. **Uncertainty in the estimates should also be quantified alongside the best estimate.** Due to the complex physical and chemical interactions that underpin contrail formation and persistence, the exact magnitude of the climate impact of contrails will likely remain more uncertain that the impact of $CO_2$.[108] The uncertainty in the impact estimate should be quantified in the MRV framework.

4. **The MRV framework should support independent validation of the impact of the contrails or the avoided impact of contrail management techniques.** Although validation of impact or avoidance is challenging because the counter-factual can be difficult to prove, it could be done through retrospective modeling or thorough remote sensing using satellite or ground-based observations.[109]

5. **The use of $CO_2$e to express the warming impact of contrails is not mandatory but helps in quantifying $CO_2$ trade-offs for contrail avoidance.** While emissions of climate pollutants are often expressed in $CO_2$e for ease of regulation, it is not a requirement for a successful MRV framework. It does, however, help in the decision-making process for contrail avoidance. If using $CO_2$e, care must be taken to avoid inadvertently creating perverse incentives that promote increases in the total climate impact of aviation.

These guidelines can help established MRV systems, which do not quantify uncertainties, to deal with the complexities of contrail impact estimation. This is further supported by recommendations for data sources and data collection.

### 6.2.1 Data collection and sources

Calculation of the contrail impact of aviation is more difficult and more uncertain than the calculation of aviation's $CO_2$ impact, requiring more significant data collection and impact calculation efforts than is needed for $CO_2$.

There are two broad categorizations of data input streams: primary data measured and reported by the aircraft operator, and secondary data collected from independent sources or chosen as default values in lieu of primary data reported by the aircraft operator.

Exhibit 20 summarizes the data quantities that should be considered to support an MRV framework for contrails. It provides a reason for the reporting requirement and offers two possible sources of the data — the ideal source and a second-best option in case the ideal solution is not possible.[110]

## Exhibit 20 Summary of Data Quantities That Should Be Considered for a Non-$CO_2$ MRV Framework

| Quantity | Reason for reporting | Best solution | Second-best option |
|---|---|---|---|
| **Flight trajectory** | Accurate positioning data informs all aspects of modeling non-$CO_2$ impacts. | GPS trajectory data recorded directly from the aircraft | Satellite-based ADS-B data or ground-based ADS-B data |
| **Humidity and temperature data** | High-quality humidity and temperature data is required to correctly quantify ISSR and model contrail impacts. | Deploying high-quality meteorological sensors for data reporting | Meteorological NWP/reanalysis data, corrected using observational data |
| **Fuel-burn rate** | The fuel-burn rate, fuel composition, and engine-specific emissions indices dictate the exhaust properties that affect contrail formation and the emission of NOx, nvPM, sulfuric particulates, and water vapor. | Instantaneous fuel-burn rate from flight sensors | Reporting the fuel burned per flight |
| **Fuel composition** | | Certificates of analysis (COAs) reporting daily airport-level fuel composition | Relying on COAs detailing the fuel composition at a given airport per batch of fuel delivered (e.g., in the EU, data reported under the ReFuelEU MRV) |
| **Engine-specific emissions** | | Fleet information reported by the airline that lists the engines used on each aircraft | Using fleet data from a secondary data provider, or using the most popular engine for an aircraft type as the default |
| **Wind conditions** | Wind conditions govern the evolution of the contrail over its lifetime. | Meteorological NWP/reanalysis data | |
| **Cloud cover** | Clouds impact the RF from contrails | Meteorological NWP/reanalysis data and satellite data | |

RMI Graphic. Source: ICCT

Wind conditions and cloud cover do not need to be directly monitored by the aircraft operators and thus would always be secondary data, collected directly from meteorological data providers. Some version of all of these quantities can be calculated without input from operators. However, certain quantities, such as fuel-burn rates, would benefit from primary data collection from the operators because otherwise they would be estimated using aircraft performance models. Further, it is not yet possible to collect certain quantities. For example, high-quality humidity data collected en route using aircraft sensors is not possible because current aircraft sensors are not sufficient. Nevertheless, they are included in the list as possible development opportunities to improve the impact estimation.

### 6.2.2 Uncertainty quantification

Another challenge in the establishment of an MRV framework is the uncertainty associated with the impact quantification. Unlike with $CO_2$, where there is low uncertainty in measuring the fuel burned for a flight and in converting that fuel consumption into $CO_2$ emissions, there is relatively high uncertainty in quantifying the climate impact of non-$CO_2$ effects. Some of this uncertainty stems from imperfect input data. The primary data collection will directly reduce some of the input uncertainty by replacing estimated data, such as fuel-burn rate, with measured quantities from aircraft operators (see Exhibit 20). Some uncertainties due to unknowns in the physical processes, such as the seeding of natural cirrus by contrails, are likely to persist. This indicates the need for a robust uncertainty quantification to be integrated into all aspects of the MRV framework. Satellite imagery will be a valuable tool for reducing uncertainty and validating data reported in monitoring reports.

Standardized uncertainty quantification methods need to be incorporated within the guidance for monitoring plans and propagated through the MRV process. Measurement uncertainties should be quantified for the parameters defined in Exhibit 20 using consistent methods for instrumentation from operators and external data providers. Uncertainties arising from imperfect modeling of physical and chemical interactions need to be quantified and carried throughout the calculation process. The impact reports submitted by operators to the verifiers should include quantification of uncertainty in the form of confidence intervals on the estimates provided. The verifier must be able to assess these uncertainty calculations as well.

Reporting the uncertainty along with the estimated impact would help determine whether operational and mitigation decisions can be made based on the reported values. Proper accounting for the uncertainties along with the estimated impacts would provide a concrete procedure to measure progress in meeting climate goals, as well as improvements in monitoring processes.

### 6.2.3 Advantages and disadvantages

While MRV systems are being used to quantify and account the emissions of other non-$CO_2$ pollutants, such as methane, they have not yet been used for SLCFs from aviation. As such, it is important to assess the benefits and drawbacks of using the MRV framework for contrails.

Creating an MRV system that annually estimates aviation's contrail impact, extending what we already know about its $CO_2$ impact, would help in understanding aviation's total contribution to climate warming. A formalized MRV framework would standardize the calculation methodology across operators and provide a consistent baseline for comparisons among operators. Standardization would also help observe year-on-year trends in the impact, which would be of scientific interest. In doing this data collection and impact estimation, operators could develop their own expertise in this area and, eventually, develop effective mitigation strategies to counter the impact. In addition to helping operators, the large-scale data collection required for the MRV framework would improve the current scientific understanding of aviation's contrail impact.

Large-scale data collection will come with an operational burden on airline operators. It will require up-skilling and, perhaps, investment in new technologies to enable the data collection. However, impact estimation can also be done automatically, without any input from airlines, as has been done by research institutions in the past.[111] Another potential disadvantage is that relying heavily on one impact estimation method may create unknown biases in the values that are reported. This is mitigated by the first guiding principle of MRV design, which states that the framework must be robust and flexible to new advancements in research.

Exhibit 21 presents potential advantages and disadvantages of the use of an MRV system for non-$CO_2$ impact measurement.

## Exhibit 21 Potential Pros and Cons of an MRV System for Non-$CO_2$ Effects

| Advantages | Disadvantages |
|---|---|
| Allows for more complete quantification of aviation climate impacts. | Poses an additional operational burden on airlines to gather relevant data quantities and conduct monitoring plans. |
| Provides a standardized approach to impact assessment across operators. | Dependence on one calculation methodology could bias the results in an unknown direction. |
| Operators can use collected data to inform decisions on effective mitigation strategies. | |
| Large-scale data collection on contrail impacts will contribute to current scientific understanding. | |

RMI Graphic. Source: ICCT

Existing MRV frameworks in various jurisdictions have established extensive data collection procedures by industry and governments in their efforts to address $CO_2$ emissions across the aviation sector. An analogous MRV framework for the climate impacts of the non-$CO_2$ effects of aviation could allow for a more complete understanding of aviation's climate impacts. An effective MRV framework could serve as a means to improve current scientific understanding and modeling through the data reported in the process. Current challenges of quantifying the contrail impact would persist until there is further development of models and data collection practices.

SECTION C

# The Future

## Contrail Avoidance Airspace Considerations and Costs

# 7. Airspace Considerations of Contrail Avoidance at Scale

## 7.1. How contrail avoidance trials are interacting with air traffic management now

An important part of running operational contrail avoidance trials is to learn more about how contrail avoidance impacts ATM operations in real life. Operational trials such as the EUROCONTROL MUAC trials,[112] in which aircraft fly around contrail-prone areas to avoid creating warming contrails, have airspace-relevant objectives such as testing the operational feasibility, understanding timing (pre-tactical and in-flight adjustments), and studying network effects.

## 7.2. How would contrail avoidance at scale impact existing air traffic management operations?

The limited number of real-life trials that have been carried out so far show some challenges for airspace management implementation.[113] These include capacity reduction to maintain safety, a significant increase in air traffic complexity, workload increase, the need for potential new or upgraded tools (to manage capacity, contrail forecasting, and more), and the fact that in-flight adjustments are more challenging to deal with than pre-tactical avoidance planned before departure.

The potential impact of contrail avoidance on existing ATM operations will depend on whether the decision is made pre-tactically or tactically in flight. In practice, the approach is likely to be a combination of both, especially because the locations of the contrail-prone areas shift over time.

In a future where contrail avoidance scales up, avoiding contrail-prone areas may lead to the concentration of air traffic in other parts of the airspace, potentially increasing congestion, especially in high-traffic areas.

Pre-tactical avoidance may require additional air traffic flow management measures to ensure that the traffic load is balanced within and across different sectors and across different times, preventing any single sector from becoming overloaded. For ATC sectors receiving additional aircraft in low-traffic scenarios, the impact would normally be minimal. However, in moderate or busy traffic conditions, capacity reductions might be necessary. This would include situations where vertical rerouting takes place within the vertical bounds of one sector in airspaces without vertical splits around the designated levels. In this case, where multiple flight levels within a sector may be subject to avoidance, the sector traffic counts may need to be closely monitored.

Tactical contrail avoidance can be initiated by the flight crew or by the ATCO. In either case, ATCOs will assess the feasibility of providing a revised clearance to avoid contrails, accounting for the surrounding traffic and any required coordination with other sectors and considering any increased operational complexity or workload implications. This adds layers of complexity to ATM operations, as ATCOs must manage more variables and coordinate closely with flight crews to implement contrail avoidance strategies.

Safety and efficiency must be maintained. Any adjustments for contrail avoidance must not compromise established safety standards and protocols.

Rerouting traffic to avoid contrails adds workload for finding safe revisions to the trajectories and can require extra coordination between ATC sectors. This is especially needed when revised flight levels differ significantly from the planned levels. If contrail avoidance measures are implemented, capacity plans must account for this to ensure traffic is managed safely and efficiently.

## 7.3. Alternative contrail avoidance process flow

For now, contrail avoidance trials mainly have taken an airline-initiated, flight-by-flight approach, as illustrated in the contrail avoidance process flow described in chapter 5.2. In ongoing projects, research is focused on understanding the impacts on ATM operation of contrail avoidance at scale. Multiple large-scale simulation activities are being conducted to understand the network effects and the extent to which ATC would be able to facilitate the airline requests, both pre-tactically and in tactical operations.[114] The aim is for ATC to facilitate the flights to fly as filed.

For oceanic flights, the aircraft operator can use the latest contrail forecast data to request a modified oceanic trajectory while the aircraft is in flight but prior to the oceanic entry point. Alternatively, the flight crew can request to climb or descend tactically at suitable points along the route. ATC would be informed that the reason for the trajectory change is for contrail avoidance and would provide the revised clearance as traffic conditions permit. Trajectory change requests would be prioritized by: (1) safety (e.g., weather avoidance, turbulence), (2) contrail avoidance, and (3) all other requests.

## 7.4. Taking a systems approach to contrail avoidance's impact on airspace operations

In the future, contrail avoidance must be integrated seamlessly into existing ATM operations to ensure safety and efficiency. This approach requires a holistic view, considering not just the direct effects of contrail avoidance on flight paths but also the cascading impacts on airspace capacity, traffic flow, and ATC workload.

To effectively measure and manage these impacts, it is crucial to develop models that simulate the behavior of the entire airspace system under different contrail avoidance scenarios. These models should account for the variability in traffic patterns, weather conditions, and airspace configurations. By doing so, stakeholders can identify potential bottlenecks, capacity reductions, and the need for additional ATC coordination. Furthermore, a systems approach facilitates the development of mitigation strategies that balance contrail avoidance with other operational priorities, ensuring that the implementation of contrail avoidance measures does not compromise overall airspace efficiency and safety.

## 7.5. How could contrail avoidance affect ATC procedures, training, and operations?

For ATC, the introduction of contrail avoidance will require enhanced coordination among different sectors and air traffic service units.

Gradually phasing in contrail avoidance would allow relevant personnel to receive training and the implementation of more advanced tools and data analysis. Ideally, contrail avoidance should be incorporated into the training syllabus of student ATCOs.

Operational changes will be necessary to support contrail avoidance. Airspace design may need to be adjusted to facilitate more flexible flight levels and routes. Free route airspace lends itself well to contrail avoidance because it effectively gives the airspace user the freedom to fly the trajectory it wants without the constraints of a fixed route structure.

Capacity planning will need to account for the impact of contrail avoidance, particularly during peak traffic times, and include contingency plans for capacity reductions and strategies to handle increased demand for certain flight levels.

Continuous improvement will be necessary, with regular updates to training programs, procedural manuals, and operational protocols to keep pace with evolving contrail avoidance strategies and technologies. Overall, implementing contrail avoidance will require integrating environmental considerations with core aviation operations, demanding significant changes to procedures, extensive training, and a commitment to continuous improvement.

# 8. Understanding Cost Parameters Involved When Scaling Contrail Avoidance in Airline Operations

Once we better understand the uncertainties surrounding contrail avoidance, have developed a suitable MRV framework, and considered potential operational updates required, we can explore the future implications of adopting contrail avoidance at scale. Two main areas of concern are integration with existing ATM services (addressed in chapter 7) and the cost of adopting solutions. This chapter examines the latter at a high level to develop an initial cost estimate and ascertain whether the cost would present a major barrier to adopting contrail avoidance solutions.

## 8.1. The estimated cost of adopting and integrating contrail avoidance solutions into existing operations

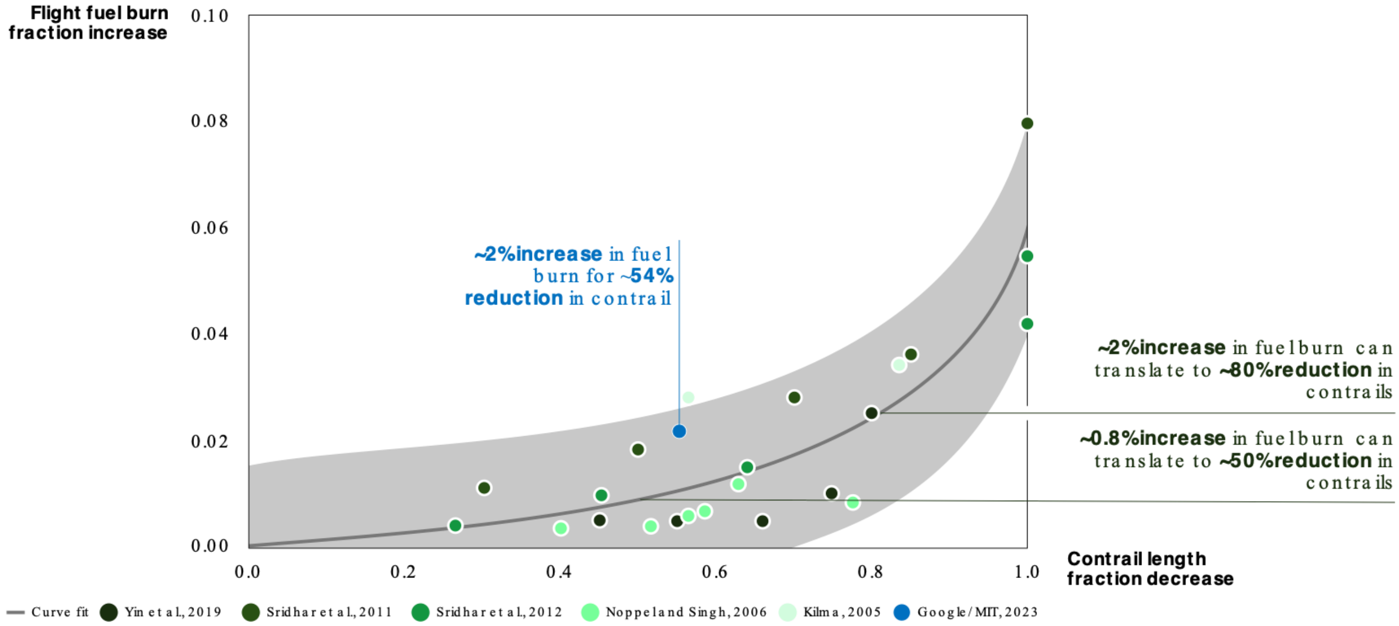
Integrating contrail avoidance solutions through navigational avoidance with an airline's operations will inevitably require additional operational expenditures (primarily on fuel) by airlines and capital investments (primarily on observation infrastructure and additional sensors) from various players. In this section, we look at each in turn.

### 8.1.1. Operational expenditures

Contrail avoidance by navigational avoidance will require airlines to address two direct operational costs: an increase in fuel burn and additional personnel and software costs to enable additional weather modeling and incorporation into flight schedules. Although the ecosystem will need to bear other operational costs (e.g., minor variation to flight durations and overflight charges), these appear relatively limited in scale by comparison.

We assume contrail avoidance is achieved in a targeted way by local rerouting to avoid specific ISSRs. Models in several studies suggest that contrail length can be substantially decreased in this way, with only limited increases in fuel burn. A meta-study of several analyses suggests that 50% reduction in contrail length can be achieved with only a 0.8% increase in fuel burn, with an 80% reduction in contrail length requiring a 2% increase in fuel burn for flight deviations (see Exhibit 22).[115]

## Exhibit 22 Fuel-Burn Cost of ISSR Avoidance when Deviation Occurs

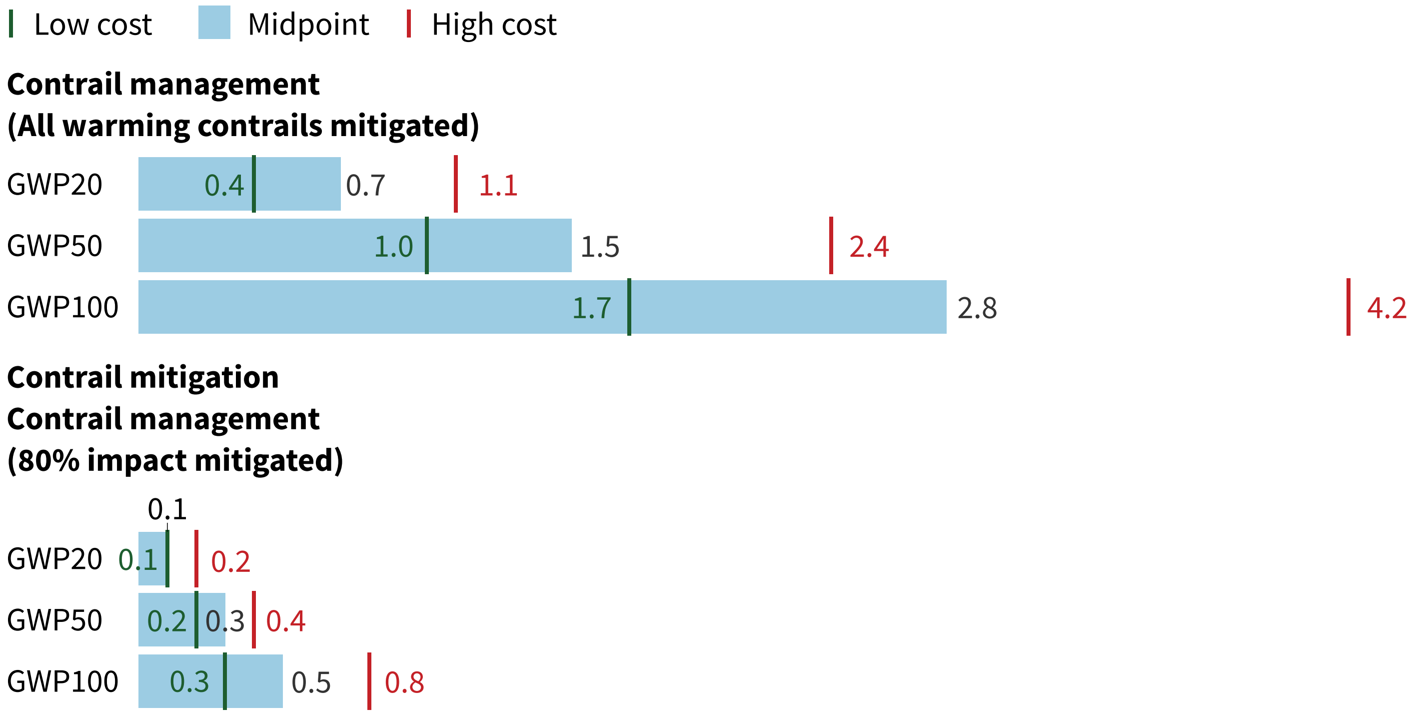



Note: Fuel burn increase applies only to flights that require deviations; at fleet level, the increased fuel burn is significantly lower
Source: Dray et al., Google, and Roland Berger

Experimental validation of these models has now begun. For example, Google, American Airlines, and Breakthrough Energy conducted flight trials demonstrating a 54% reduction in contrail formation at the cost of a 2% fuel-burn increase across 35 pairs of flights.[116] Because only a small share of flights need to reroute (most flights do not enter ISSRs),[117] this estimate may be treated as an upper bound, and as a potentially significant overestimate of total fuel-burn impact. Considering that not all flights would need such diversion, Google and American Airlines estimated a 0.3% fleet-wide fuel-burn increase based on their study.[118] Other recent studies from FLIGHTKEYS and SATAVIA suggest similarly low fuel-burn increases at +0.11% at a fleet level (achieving a 73% reduction in RF) and <0.4% (saving >40 t $CO_2$e per flight) on optimized flights, respectively, demonstrating the limited fuel-burn impact expected from contrail avoidance.[119]

In Exhibit 23 shows some estimates for the cost of at-scale (fleet level) contrail avoidance across a variety of effectiveness scenarios at a constant fuel-burn penalty of 2%. In the middle case (based on the Google/American Airlines study and Exhibit 23 source research), assumptions include a 55% reduction in contrail and contrail cirrus RF, with a lower bound of 40% and an upper bound of 90%.[120] As an additional case, because only 14% of flights generate warming contrails and only 2% of flights may be responsible for 80% of warming contrails,[121] we look at the cost of a more targeted strategy focused solely on flights expected to create persistent warming contrails. Given the ongoing debate about the appropriate time horizon (see chapter 4), we have estimated the cost of abatement in carbon equivalence for GWP on 20-, 50-, and 100-year time horizons, considering the relative impact of contrails and contrail cirrus versus $CO_2$.[122]

## Exhibit 23 Fuel Cost per Ton of $CO_2e$ Abated through Contrail Avoidance




Note: Values depicted represent $/$tCO_2e$
Source: Roland Berger

Overall, even over the longest time horizons, where the impact of short-lived contrails is comparatively limited, and on the upper bound high-cost case considered, the costs for environmental impact abatement are less than $5/$tCO_2e$. This cost is relatively low when compared with, for example, the shadow price of carbon or the social price of carbon. See Section 8.2. for a direct comparison.

In line with what has so far been demonstrated experimentally, this prediction includes a probability that, for an individual flight that burns extra fuel to avoid potential contrail formation, the diversion is unsuccessful. For example, a contrail may still be produced; conversely, it is also possible that had the diversion not been performed, a contrail may not have been produced. For these false positive and false negative probabilities to be mitigated, weather (and specifically ISSR) forecasting methodologies must be improved, and MRV schemes and data from observation must be leveraged to continuously improve the methodologies used for weather modeling and contrail avoidance.

On top of additional fuel costs, operationalizing contrail avoidance solutions with airlines and ATC will also require increased spend on software — to upgrade flight planning systems and flight management systems to include contrail avoidance-related data. These data costs include future highly detailed weather predictions, more accurate flight position data, precise engine emissions, accurate fuel composition data, and potentially using machine learning/AI models, which require high-performance computing. Additional information system costs are also expected at airlines and ATC to enable sharing of data (e.g., observed contrails or measured humidity) between groups. These semifixed costs are considered further in Section 8.1.2.

In addition to the direct operational costs from fuel and software, there are further operational considerations when engaging in contrail avoidance — all similar to current considerations undertaken to avoid turbulence. First, the potential increase in flight duration must be accounted for, potentially leading to (minor) adjustments in flight schedules and slots. However, this is expected to be relatively limited, with variations on the order of ±1%,[123] substantially less significant than airlines' daily operational challenges.

Second, extra fuel requirements may need to be added to the preflight planning to account for potential en route trajectory changes to avoid ISSRs. Thirdly, from a planning perspective, preparing to reroute to avoid ISSRs needs to be added to the preflight checklist and may also become an additional mid-flight responsibility. This implies additional training for pilots and dispatchers to support making decisions on alternative flight paths while ensuring that adverse weather conditions (e.g., clear air turbulence) are still avoided to ensure passenger safety.

Last, contrail avoidance will inevitably result in increased workload and training for ATC, where controllers will need to respond to pilots' rerouting requests while still maintaining necessary, safe aircraft separation and smooth traffic flow (see chapter 7).

### 8.1.2. Infrastructure and capital expenditures

There are two major categories of capital expenditure required: spending toward equipping aircraft with sensors to continuously detect ISSRs (e.g., humidity sensors), and spending to build the required observation infrastructure (satellite, in-flight, and ground based) to monitor the atmosphere for ISSRs continuously, and to track the formation and life cycles of formed contrails. Such infrastructure would not only be required to gather the necessary information for airlines and ATCOs to develop flight plans and navigate to mitigate contrails, but also help further data gathering to continuously improve contrail science.

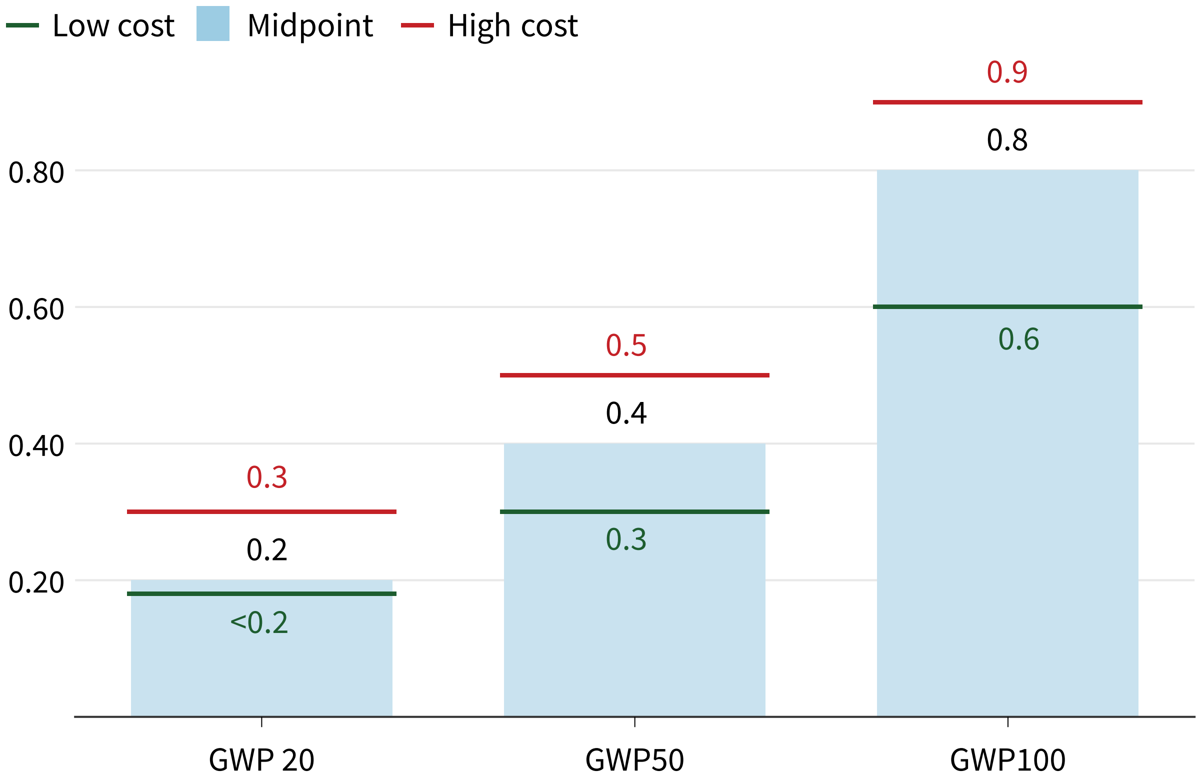
Between the investment required in aircraft humidity sensors and satellite-based observation infrastructure, the total investment may be on the order of $5 billion–$8 billion every 10 years (for detailed calculations, see Appendix D). While this is a substantial figure, it is worth putting in context of the total anticipated cost for aviation's transition to net-zero $CO_2$ — approximately $5 trillion in total, or about $180 billion per year, according to IATA's high-end estimate.[124]

Another way to consider this cost on a comparative basis is per $tCO_2e$ by amortizing the costs over the assumed renewal cycle of 10 years. On this basis, this up-front expense can be amortized as between $500 million–$800 million per year.

In recognition of the current lack of consensus on which $CO_2e$ metric to use for contrails, Exhibit 24 visualizes the cost across GWP20, GWP50, and GWP100 bases. In GWP20 terms, the cost would be relatively low at $0.2–$0.3/$tCO_2e$, while in GWP100 terms, the cost would be approximated at $0.6–$0.9/$tCO_2e$.

Exhibit 24

**Estimated Capital Expenditures, Amortized on a $ per $tCO_2e$ Basis, 2040**



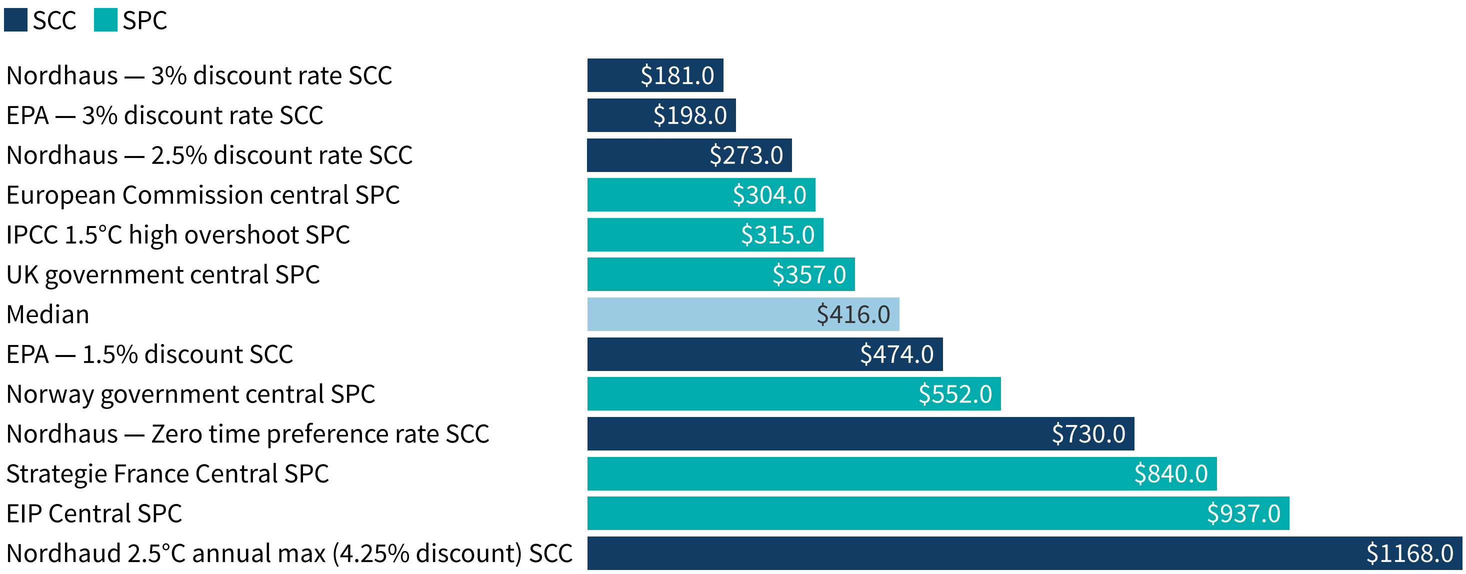

Note: Values depicted represent $/tCO2e, GWPX
Source: Roland Berger

Note that there is an additional category of expenditures in the upgrade to processes and tools required for airlines and ATC providers to include contrails management in flight planning and navigation and in building the systems required for information sharing (such as humidity data from aircraft sensors, observation data from satellite-, in-flight, and ground-based sources, etc.). While it is possible to set up several such systems, there is expected to be significant efficiency in a shared weather/ISSR notification service, which would necessitate further set-up expenses. These expenses are expected to be semi-fixed, consisting of some fixed cost components (data centers, initial software development, and initial personnel training) and some variable components (energy costs, maintenance, ongoing personnel training). Depending on the solutions that are ultimately implemented, these systems may also require investment in machine learning/AI to process the significant volumes of data gathered from disparate sources and discern patterns to provide recommendations to airlines and ATCOs in real time. However, based on discussions with various players across the ecosystem, we anticipate such costs to be significantly lower than the major categories in operational expenses (incremental fuel costs) and capital expenditures (observation satellites and sensors). As such, they are not estimated here in depth.

## 8.2. The relative cost of contrail avoidance

To understand whether cost should be considered a barrier to pursuing contrail avoidance, we compare the operational costs it would require against the cost to society of $CO_2$ emissions. This comparison is based on long-term forecasts of the expected cost to society of abating the carbon in line with emissions and climate change targets — the shadow price of carbon (SPC) — or the present value of the damage associated with the additional ton of emissions, known as the social cost of carbon (SCC). Estimates for these vary significantly (Exhibit 25), between \$200 and \$1,100/t $CO_2$ (in 2019 prices), depending largely on the chosen climate scenario and discount rate assumptions.

## Exhibit 25 **Estimated Value of a Ton of $CO_2$ Emitted in 2050**




Note: Values based on 2019 prices in \$
Source: Oxford Economics, EPA, EIB, Nordhaus et al., European Comission, IPCC, UK government, Norway government, Strategie France, Roland Berger

As set out in Section 8.1.1., we expect the incremental operational costs from fuel burn to range from \$1 to \$5/t $CO_2e$ if pursued on all flights forming warming contrails (or <\$1/t $CO_2e$ if targeted only at flights producing 80% of warming contrails).[vii] These costs vary depending on the efficacy of management solutions and time horizon of the climate metric chosen (noting the high levels of uncertainty on the climate impact of contrails, and that certain additional cost elements, such as the required labor and software costs, have not been fully quantified in this estimate). Additionally, as discussed in Section 8.1.2., the additional cost of capital expenditures is expected to be in the range of \$0.2–\$1/t $CO_2e$. Thus, the expenditure on the key areas of increased fuel burn and investment in observation infrastructure may be \$1–\$6/t $CO_2e$ on a conservative basis, or lower if the mitigation is performed on just the limited number of warming contrail flights. Other costs, such as pilot training and ATC personnel, need to be quantified and may be significant, although they appear likely to be significantly below the price of SCC and SPC.

Compared with the shadow or social costs of carbon, these estimates are two orders of magnitude lower. This would suggest that contrail avoidance, regardless of which climate metric is chosen, could be a highly cost-effective means of mitigating the climate impact of aviation relative to the externalities, in parallel to the ongoing decarbonization efforts of airlines.

**vii** Albeit excluding additional operational costs from non-fuel burn areas (e.g., software, ATC and flight controller labor).

# Recommendations

## Address non-$CO_2$ impacts in addition to efforts to decarbonize aviation

Managing contrails and other non-$CO_2$ effects of aviation should be viewed as additional to the ongoing decarbonization of aviation — they are not interchangeable solutions. It is critical that contrail management does not hinder or come at the expense of efforts to decarbonize aviation. The two should not be seen as trade-offs but work to bring down both $CO_2$ emissions and non-$CO_2$ effects in parallel.

## Scale up real-world flight trials to help refine contrail avoidance strategies and improve prediction model accuracy

Although learnings from early real-world trials and research in recent years are encouraging, more work is needed to better understand the climate impact of contrails and improve potential contrail avoidance solutions. An increase in commercial operator participation in large-scale flight trials can support the collection of critical data needed to better understand the warming impact of contrails. Large-scale flight trials conducted in collaboration with stakeholders from across the aviation value chain can also enable greater knowledge sharing and advance validation processes critical to improving contrail prediction models. Additional trials can also help airlines, flight planners, and airspace managers obtain operational know-how, gain experience with integrating contrail avoidance into operations and further automating processes within flight planning tools, and support the evaluation of airspace implications of contrail avoidance.

## Advance research on the full climate impact of contrails

To ensure better decision-making on when to avoid contrails, certainty about the full climate impact of contrails must be increased. This can be done through investment in additional atmospheric science research and the development of better weather data to narrow the uncertainty bounds of how much contrails impact climate warming.

## Improve prediction models

Additional quality data inputs are needed to improve the accuracy of contrail prediction: better weather models, advanced humidity sensors on aircraft, and enhanced satellite imagery. Additional flight trials and validation systems for ground-based, in-flight, and satellite-based observations of contrails can help validate and improve prediction models.

## Continue to investigate the role of advanced fuels and technology on contrail impacts

In addition to contrail avoidance, there are also opportunities to further understand the potential benefit that different types of SAFs and fuels with lower aromatic content provide against contrail impact. It will also be important to understand the non-$CO_2$ effects connected to newer, cleaner engines as well as future propulsion technologies such as hydrogen-powered aircraft and their potential contrail impacts.

## Scaling research through potential financial incentives and policy measures

Large-scale contrail avoidance trials can be supported by funding mechanisms such as the European Innovation Fund, which covers up to 60% of the cost of eligible projects. Additional research and development funding opportunities that could help advance contrail avoidance could include:

- Flight planning providers could receive grants to modernize software systems that integrate contrail forecast and verification models.
- Aircraft manufacturers, aircraft engine manufacturers, and aircraft operators could apply for funding to equip aircraft with state-of-the-art humidity sensors as well as funding to maintain and calibrate systems.
- Grant funding could be allocated for additional research to measure the impact of low-aromatic fuels on contrail formation.
- Satellite developers and weather data providers could receive grants to advance satellite imagery capabilities, enabling easier tracking of persistent contrails as they evolve.

## Undertake large-scale airspace simulations of contrail avoidance

As contrail avoidance scales up, so do the airspace implications. ATM needs to be included and prioritized in research, simulations, and trials to prepare for possible future airspace challenges like capacity constraints and congestion issues and to adapt systems and processes over time. As trials scale up, ATM will benefit from adjusting airspace design for more flexible flight levels and routes while also doing capacity planning to account for contrail avoidance impacts during peak times. Developing models to simulate airspace behavior under different contrail avoidance scenarios will help identify potential bottlenecks and capacity reductions, helping in creation of mitigation strategies that balance contrail avoidance with operational priorities.

## Identify and adjust thresholds for contrail avoidance

To standardize the decision-making process of whether to avoid a contrail, it will be important to reach an agreement on which climate metric to use when comparing contrail-induced warming to possible extra fuel spent and $CO_2$ emitted. Developing and deciding upon a shared methodology (i.e., a low-medium-high contrail decision matrix) can lead to an operational approach for application across industry trials.

## Understand the full cost of contrail avoidance

There are indicators that contrail avoidance is a very low-cost climate solution compared with other climate solutions in aviation. While there is an idea of the limited amount of extra fuel needed to avoid warming contrails, other operational costs — and estimated capital investments — need to be fully analyzed and understood to accurately assess the full potential cost of implementing contrail avoidance in operations.

## Establish effective MRV frameworks

Developing non-$CO_2$ MRV frameworks are one way of measuring and recording contrail impacts; if designed with sufficient data, they could inform contrail abatement strategies in the future. These frameworks will evolve with the progression of scientific research. Large-scale data collection and impact assessment will contribute to a more complete understanding of aviation climate impacts.

## Communicate the full climate impact of aviation

More operators are publicly addressing the climate impact of non-$CO_2$ effects and the kinds of action needed to mitigate these impacts. The warming created by $CO_2$ emissions from aircraft engines is well established for most travelers; however, there is a knowledge gap when it comes to the additional non-$CO_2$ effects of aviation, including those from contrails. Consistent and accurate public messaging about contrails, their climate impact, and ways to manage them is needed.

# Appendices

# Appendix A: Understanding Radiative Forcing

The Earth's atmosphere is warming because human influences are affecting the radiative balance in the atmosphere, termed radiative forcing (RF). RF quantifies the net change in energy in the Earth system at a point in time, i.e., how much energy the Earth absorbs from the sun versus how much it emits back into space. Under stable climate conditions, the Earth's energy system is, on average, balanced, meaning that the planet radiates as much energy back into space as it absorbs.[125] Since the Industrial Revolution, however, humans have altered this equilibrium, introducing drivers of climate change, especially GHG emissions, that increase energy absorption. RF is thus expressed as the difference in the energy balance between present day and preindustrial times — typically the year 1750 — in energy per unit area, i.e., W per $m^2$.[126]

Because the atmosphere is a well-mixed pool of gases, RF is usually reported as a global average over the Earth's surface, but it is possible to estimate local RF for smaller geographic regions.[127] Scientists estimate RF at the top of the atmosphere. Upon emission of a forcing agent, the change in net energy sets in motion a series of adjustment processes throughout the climate system.[128] Researchers usually allow stratospheric temperatures to stabilize before estimating RF and hold tropospheric and surface temperatures fixed in their model. Allowing stratospheric temperatures to adjust makes RF a better indicator of the eventual temperature response to the energy forcing.[129] All emissions metrics use RF estimates as inputs into either reduced-complexity climate models or in equations derived from more complex models.[130]

From this basic calculation of RF, researchers can add complexity to account for relevant real-world effects. As outlined above, a climate forcer can have a variety of knock-on effects in different parts of the climate system, e.g., cloud cover. Changes in cloud cover in turn affect the net energy balance of the climate system since they can reflect solar energy back into space or reflect heat radiation back to the surface. To capture rapid adjustments in the climate system, effective radiative forcing (ERF) expands upon RF, allowing all stratospheric and tropospheric conditions to adjust in response to a GHG emission while keeping land and sea surface conditions fixed.[131] This change makes ERF a more accurate input into calculations of the magnitude of the eventual climate response for forcing agents whose effect plays out largely through their effects on clouds, such as aerosols and contrails.[132]

Estimating ERF requires more complex modeling because researchers must account for interactions among different forcing agents in the troposphere, some of which might not be well understood.[133] Since its Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) has started reporting ERF instead of RF values, primarily because ERF is a better predictor of temperature change, especially for aerosols.[134] This change in IPCC policy has put renewed focus on improving the modeling of and the confidence in ERF estimates in recent years. The Sixth Assessment Report revised many ERF estimates.[135]

The main difference between RF, ERF, and other less-common sub-definitions of RF is that part of an emission's effect on the climate is defined as a direct impact and what is simply a climate feedback. When immediate effects and longer-term feedbacks like cloud adjustments counteract each other, these forcing values can differ significantly across forcers.[136] For the purposes of deciding whether to avoid creation of contrail, the RF values estimated for contrails should be adjusted to ERF.

# Appendix B: Pros and Cons of Different Operational Decision Metrics

## Global Warming Potential

Global warming potential (GWP) is the primary climate metric — alongside global temperature potential (GTP) — reported by the IPCC.[137] Somewhat confusingly, however, it is not a measure of warming or temperature change but of the total energy trapped in the Earth's system over a time horizon. It is calculated by integrating the forcing estimate (ERF or RF) of a pulse emission of a gas over the time horizon, and then dividing by the integrated forcing of the same mass of a $CO_2$ emission.[138] GWP was the first and remains one of the simplest metrics to assess the relative impact of GHG emissions. Given forcing estimates, it is easy to compute.

**GWP — Pros:** While critics have objected to GWP since its introduction, there are good reasons for its prevalence. An important aspect is its simplicity. It is easy to calculate and requires only two sets of parameters: RF estimates and atmospheric lifetimes. Other climate metrics, in contrast, require complex climate modeling. If necessary, it is easy to quickly compute GWP for a variety of time horizons, even if such calculations are rare.

GWP dominates climate discourse due to inertia. It was the first widely used climate metric and remains the metric of choice. Even if a clearly superior metric emerges, i.e., the costs and dangers of rewriting international climate treaties would be immense.[139] Private firms and governments expect one other to report GHG emissions using GWP100 values, the common language that allows comparisons between gasses, entities, and scenarios. The use of alternative metrics, therefore, is usually restricted to niche applications outside of the broader network of reporting and accounting frameworks.

**GWP — Cons:** Objections to GWP begin with the very nomenclature of the metric. Indeed, the naive interpretation is far removed from its real meaning.[140] The quantity that GWP measures, the total energy trapped in the Earth's energy system over time, has little to do with temperature change. Averaged over time, the Earth seeks to balance the energy system and radiates excess incoming solar energy back into space.[141] The sum of incoming radiation that GWP measures — ignoring stabilization effects of the climate system — has no real physical meaning. GWP therefore has little to do with the true warming impact of a forcing agent.

Another criticism is that GWP values for short-lived climate forcers (SLCFs), including contrails, are meaningless beyond a certain time horizon. For example, after 40 years, more than 95% of the methane from an emission has dissipated, and its GWP40 value is 55, yet its GWP100 value is 28. This difference does not effectively represent the change in the effect on temperature of the methane emission. In fact, the difference is almost entirely driven by the increase in the absolute global warming potential (AGWP) value for $CO_2$ in the denominator of the calculation.[142] The warming caused by the methane emission remains basically unchanged between year 40 and year 100.

These two drawbacks explain why GWP is ill-suited to track temperature changes. One example, provided by Working Group 1 of the Sixth Assessment Report, imagines a world in which the emissions of SLCFs have stopped increasing but remain above zero. In this case, global mean temperature would stabilize, even as emissions measured in GWP100 carbon dioxide equivalent ($CO_2e$) continue to rise.[143] In the context of multi-gas treaties like the Kyoto Protocol and the Paris Climate Agreement, treating different forcing agents interchangeably based on GWP values leaves us with a wide range of potential future temperature outcomes depending on the exact mix of forcing agents used to achieve different nationally determined contributions.[144] Many of these scenarios lie beyond the stated temperature goals of either agreement.

## Global Warming Potential* — reasons for exclusion

GWP* is a step-pulse metric that tries to remedy a common criticism of integrated metrics such as GWP. While the metric is mentioned here, it will not be actively considered, because it is not useful in the context of contrail mitigation. Almost all the criticisms laid out for GWP* in general also apply to contrails.[145]

## Cumulative Climate Impact and Instantaneous Climate Impact

Two dynamic metrics that have been proposed are the cumulative climate impact (CCI) and instantaneous climate impact (ICI).[146] CCI is the integrated climate forcing between the time of emission and the target year. CCI can therefore be thought of as a dynamic version of GWP for which the time horizon changes based on the year of emission, illustrated in Exhibit 16. ICI is the RF of the climate forcer in the target year.

**CCI and ICI — Pros:** Unlike other proposed dynamic metrics that require wide-ranging assumptions about rates of technological change or the cost of mitigation, calculating CCI and ICI only requires a target stabilization year.[147] The other inputs are the same as for GWP. Some research has shown that CCI and ICI are better at preventing large overshoots of temperature targets than static metrics under a wide variety of emission scenarios.[148] However, the study of CCI and ICI has so far mainly focused on assessing the impact of methane-emitting technologies. Similar studies for the aviation sector could help paint a clearer picture of how the use of these metrics with climate forcers that have much shorter lifetimes than methane.

**CCI and ICI — Cons:** The main issue for using CCI or ICI is making the metric comparable across different users. Users must agree on target year, and arriving at this decision requires agreeing on complicated assumptions on ever-changing factors like emissions pathways, so the target year of CCI/ICI might need to be adjusted often. The need for adjustments of the target year could also potentially be difficult to communicate to the public and policymakers. Any climate impacts that occur beyond the target stabilization year are not considered, which could pose issues in later years.

## Global Temperature Potential

GTP is the other advanced climate metric reported by the IPCC aside from GWP. As the name suggests, it quantifies the change in global mean surface temperature at a certain point in the future. For example, the GTP100 for nitrous oxide ($N_2O$) estimates the temperature change in 100 years due to a pulse emission of a $N_2O$ relative to the change in temperature due to a pulse emission of 1 kg of $CO_2$. Since GTP only reports the temperature change in Kelvin at the end of the time horizon, it provides no information about the climate impact during the time horizon, hence GTP is a so-called endpoint metric.

GWP and GTP are closely connected, but GTP treats incoming radiation slightly differently. By integrating forcing over the time horizon, GWP implicitly assumes that all excess radiation is stored on the Earth's surface. In reality, energy is transferred between different sinks in the climate system, most notably the different layers of the ocean.[149] By modeling the more complex elements of the climate response to changes in net energy, the climate impact predicted by GTP tracks temperature better than GWP, but the additional modeling assumptions also make the model yield more variable results.[150] The 90% confidence interval for the GTP of methane, for example, spans ±40% of the GWP value, whereas the interval for GTP is ±70%.[151]

**GTP — Pros:** GTP tries to correct the main shortcoming of GWP, namely, its inadequacy in tracking temperature. Rather than incorporating a permanent memory of excess RF, as implied by GWP, GTP accounts for the transfer of heat between various heat sinks in the Earth system, such as the shallow and deep oceans.[152]

In comparing the temperature impacts predicted by the GTP equations with the impacts estimated from more complex and complete climate models, we see that GTP follows the dynamics of temperature change in response to a forcing agent very well. The temperature peak time and decay rates are almost identical to those of the complex model, even though GTP tends to overestimate the temperature effect.[153] Nevertheless, GTP is a reasonable middle ground between sophisticated temperature tracking and relatively low computational complexity. More complex climate models, although more accurate, are computationally too expensive for day-to-day airline operations.

Another advantage of GTP over GWP is that by removing the unrealistic permanent memory of excess energy assumed by GWP calculations, GTP is significantly better suited for evaluating the role of SLCFs, which include contrails.[154] However, this advantage mostly applies to GTP values using a dynamic time horizon, which shorten as the target year approaches. A variation of GTP is dynamic GTP, which is an effective tool to evaluate different mitigation strategies that are aimed at limiting temperature increases below a certain threshold. As the time horizon shortens, the importance of SLCFs like contrail cirrus increases, as these are more likely to push temperatures above the threshold.[155]

**GTP — Cons:** The major disadvantage of GTP is the inherent uncertainty in its estimates of $CO_2$e. GTP values are highly sensitive to even small changes in assumptions about heat exchange between the different heat sinks in the model. GTP estimates therefore have a larger uncertainty than GWP.[156]

While the differences between theoretical and realized warming trajectories using $CO_2$e GTP values are significantly smaller than when using GWP, there is still uncertainty in warming pathways before and after the target year because GTP's endpoint design leaves us unable to assess impacts outside out the chosen endpoint.[157] For example, a scenario with a large amount of short-lived emissions could lead to warming levels above the stabilization temperature predicted by GTP in the years before the endpoint, which could have unforeseen consequences.

## Average Temperature Response

A recently developed climate metric is the average temperature response (ATR). It has gained traction among the scientific community, especially the German Aerospace Center (DLR).[158] Although it was originally designed to assess the impact of aircraft designs, it is now used both in fleet and single flights assessments.[159] Since it measures the same climate impact as GTP, the two are closely connected and can be estimated using reduced-complexity climate models such as AirClim.[160] GTP quantifies the relative change in global mean surface temperature at a certain point in the future, whereas ATR quantifies the relative average change in temperature over the time horizon. Put simply, an ATR20 would sum all GTP values from years 1 to 20 and then divide by 20 if GTP and ATR are computed from the same model. Proponents of ATR note that it gives a more holistic picture of the temperature effect of an emission, as opposed to the simple snapshot that GTP provides.[161]

**ATR — Pros:** ATR tries to solve the issues common to both GWP and GTP. Like GTP, ATR accounts for heat transfer between Earth's various heat sinks and tracks temperature much more accurately than GWP. Unlike GTP, ATR considers the temperature over the entire time horizon rather than the simple snapshot at the endpoint. When using ATR for mitigation, the exact mix of climate forcers therefore has a less pronounced effect, since ATR accounts for the different temporal evolutions of the climate forcers considered.[162] There is thus less uncertainty in the exact warming pathway than when using GTP.

**ATR — Cons:** If the primary aim of comparing climate forcers is to keep temperatures under a certain threshold, such as those of the Paris Climate Agreement, ATR is less useful because averaging temperature changes over the time horizon obscures temperature peaks. Because of this disadvantage, ATR might be poorly suited for when making mitigation decisions in an operations context. ATR is poorly equipped to deal with temperature targets, especially since it was originally created for engine design purposes.[163]

# Appendix C: Development of an MRV Framework for Non-$CO_2$ Impact in the EU

In May 2023, the European Parliament and Council issued a directive that, among other changes, will require aircraft operators to annually report the non-$CO_2$ effects of their activities starting January 1, 2025.[164] In support of this, the European Commission is to adopt a monitoring, reporting, and verification (MRV) framework by August 31, 2024. The directive explicitly states the request to calculate a $CO_2$e value per flight; however, it only requires reporting to occur once a year. It also charges the European Commission to submit an annual report, from 2026 onward, on the results of the MRV framework. This is to culminate at the end of 2027 with a report and, if deemed appropriate, a legislative proposal to include the non-$CO_2$ impacts of aviation under the EU's Emissions Trading System.

The legal text of the EU MRV has not been released at the time of writing this document and, as such, is not detailed in this report.

# Appendix D: Calculated Estimates for Capital Expenditures

The precise cost of a shipset of additional sensors on aircraft is still unknown. These sensors would be required to continuously gather accurate data on the air's water vapor content and temperature. With enough aircraft, gathering such information could help develop a continuously updated mosaic of atmospheric humidity, which is expected to be necessary for wide-scale tracking and forecasting of ice supersaturated regions (ISSRs).

The cost to enable this includes the cost per sensor (with the requisite humidity sensors still under development) and the number of sensors per aircraft. In addition, it is as yet unknown the number of aircraft that would need to be equipped with sensors to provide sufficient data gathering coverage across the global airspace. However, for this analysis, we chose to take a conservative view, assuming a relatively high cost for sensors and that the whole global aircraft fleet would need to be equipped:

- Today, the average aerospace-grade sensor costs approximately $1,500–$2,000 each, with higher-end sensors (e.g., accelerometers, flow sensors) costing $5,000–$10,000 per sensor.
- By comparison, the International Air Transport Association (IATA) recently estimated that the shipset cost of the high-end humidity sensors that would be required at $20,000–$180,000.[165] Simply assuming the midpoint in IATA's estimate, we take $100,000 per sensor, with the assumption of one sensor per aircraft and a replacement lifecycle of 10 years.
- Note that over time, the costs are likely to reduce significantly, especially since such sensors are currently only installed on approximately 140 aircraft globally, and it can be reasonably assumed that per-sensor and per-shipset costs would reduce significantly if the solution were scaled up to the fleet level, owing to economies of scale (e.g., in materials, manufacturing, etc.).
- However, there are several unknowns, including maintenance costs and whether the replacement frequency of once every 10 years is accurate — thus, we continue with the assumption of $100,000 per shipset.
- By 2040, there are expected to be approximately 40,000 aircraft in service (though estimates vary).
- Finally, we also take a very conservative assumption that 50%–100% of the global aircraft fleet would require a full shipset of sensors, and thus come to an industry-wide estimate of $2 billion–$4 billion in expenditures every 10 years.
    - Note that there is not yet consensus on the number of aircraft required per region to gather this data, with some estimates as low as tens or hundreds of aircraft per region.
    - Nevertheless, for the estimate here, this highly conservative assumption may compensate for the significant unknowns in the cost of a shipset of sensors, or the maintenance and replacement requirements.

Note that this estimate, though conservative, does not include any assumptions about weight or drag penalties incurred due to the presence of onboard sensors. It is also currently anticipated these installations could be conducted during standard aircraft C-checks (which last three weeks and are usually carried out every 18–24 months for most type of aircraft). Thus, no additional scheduled maintenance breaks would be required, preventing unnecessary operational burden on airlines, albeit some additional labor and equipment costs would be incurred during these shop visits.

Second, regarding observation infrastructure: ground-based, in-flight, and satellite-based observation is likely to be required. Ground-based infrastructure requirements are expected to be small, with existing infrastructure generally sufficient, albeit with the addition of visual and infrared spectrum cameras. In-flight observation is not expected to require any infrastructural changes, but rather an additional task for the (already very busy) flight crew, using existing equipment. From a capital expenditures perspective, both ground-based and in-flight infrastructure are expected to cost much less than the corresponding satellite-based infrastructure and are thus not quantified here.

Considering satellite-based infrastructure, this report's authors made the following assumptions to develop an estimate of the Earth observation capabilities required:

- Diverse set of sensors, able to reliably image contrails, including optical and infrared spectrums and hyperspectral capabilities

- Quasi-real-time observation of aircraft flight paths to enable tracking of the formation and life cycle of contrails

- High coverage of the Earth's surface area to cover both high-flight-density regions, and long-lasting contrails, which may drift far from the original formation location due to wind conditions

- Sufficient resolution to characterize contrails

We considered three broad options to achieve the above:

1. The use of existing "conventional" Earth observation satellites (e.g., Airbus's Pleiades or satellites from the U.S. Geological Survey's Landsat program) in cases where existing data can be leveraged or spare bandwidth can be allocated for contrail observation.

2. The use of new weather satellites in geostationary orbits (e.g., GOES-16), which provide wide coverage but necessitate large satellite systems with very expensive launch and observation equipment to achieve the resolution requirements (including ground stations to process data and operate the satellites). These satellites would have long life cycles (e.g., 10–20 years).

3. The use of a new constellation of small satellites (e.g., <50kg each) in low Earth orbit (allowing low revisit periods and high redundancy), with relatively lower launch costs per satellite and relatively more cost-effective and smaller, lighter observation equipment sensors. While this allows each individual satellite to be significantly lighter and less costly, it would require a large number of satellites to allow high-frequency revisit, with relatively shorter life cycles (e.g., two to three years) necessitating regular launches of replacement satellites (like what is already being done by Starlink).

If existing assets are used (as per Option 1), the incremental investment would be very low. Indeed, any realistic solution would certainly leverage Option 1 to an extent before any significant sums are spent, considering what data from existing satellites (both civilian and military) can be leveraged to mitigate some cost.

However, taking a more conservative approach, if we assume that Option 3 is chosen with a new constellation of satellites for contrail observation, expert estimates suggest that a constellation of 200 satellites could be deployed to achieve the coverage and revisit requirements, supported by ground infrastructure for data gathering, processing, and satellite management.[166] Conservatively assuming a cost of $3 million–$4 million per satellite, and a two to three year life cycle (i.e., full replacement of the entire fleet every two to three years), a total of $600 million–$800 million would need to be spent every two to three years — or $2.4 billion–$3.2 billion every 10 years. (Note that this is considered a conservative estimate because the cost of Earth observation satellites is expected to decline considerably, and a fleet of this size would also significantly benefit from economies of scale). Assuming then an additional 25% cost for ground infrastructure, with a rough maintenance timeline of about 10 years, the total cost can be estimated as approximately $3 billion–$4 billion to be spent about every 10 years.

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