Cover Sheet

Climate equivalence metrics for airline contrail mitigation

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Abstract

The aviation sector faces a significant challenge in mitigating climate change due to the dual impact of CO_2 emissions and contrail formation. Contrails, which form under specific atmospheric conditions, contribute to global warming. Mitigating contrails, however, can require flight path diversions, leading to increased fuel consumption and CO_2 emissions. This study evaluates various climate equivalence metrics that can be used to quantify these impacts in common units. The analysis involves a comprehensive survey of existing metrics, criteria for their selection, and a framework for decision-making regarding contrail avoidance. Using a representative flight as an illustration, the research highlights the implications of different metrics on the decision to divert flights to minimize climate impact. The study emphasizes the importance of integrating both short-term and long-term climate impacts in aviation policy and provides a decision matrix to guide airline operators. This work is crucial for developing effective mitigation strategies that align with global climate goals, considering the rapid growth of air traffic and its substantial contribution to radiative forcing. The findings support the adoption of informed, metric-based guidelines for contrail avoidance, ensuring sustainable aviation practices.

1. Introduction

1.1 Motivation

Contrails present a dilemma for mitigating climate change in the aviation sector. Some flights can avoid creating contrails by diverting their paths but at the expense of increased fuel usage. Whether the net effect of such diversions is beneficial depends on several factors, especially how the two outcomes (create contrails *vs.* divert) are measured on a common scale. This manuscript surveys the options for climate metrics, suggests criteria for choosing among them, and illustrates the decision space with a representative flight. Airline operators require rules for guiding flight-by-flight solutions to this dilemma, informed by carefully selected climate metrics.

Aviation contributes to climate change through multiple mechanisms. The combustion of fossil fuels emits a variety of greenhouse gasses (GHG), including CO_2, water vapor, NO_X, and SO_4, and climate pollutants, such as soot, or black carbon[1]. In certain regions of the atmosphere, water vapor, soot, and aerosols mix to form line-shaped ice clouds (contrails) that can persist and spread into cirrus clouds (contrail-cirrus). These contrails absorb and re-emit long-wave radiation from the Earth, which is greater than the short-wave solar radiation they reflect[2]. The net positive radiative forcing (RF) from contrails (or condensation trails) is estimated to exceed the RF from emitted GHG, perhaps accounting for 57% of the effective radiative forcing (ERF) from aviation[3][4]. Balancing mitigation efforts between these two mechanisms, however, also requires recognizing the disparate time horizons over which they occur.

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. Because of the long residence times of GHG in the atmosphere, the climate effects of fossil fuel combustion will be felt for hundreds to thousands of years. The climate effects of contrails dissipate in hours. Yet low-GHG fuels are a distant prospect, whereas airline operators have current tools at their disposal to begin avoiding contrail formation. Quickly deploying these tools could provide short-term mitigation while buying time for longer term solutions. Rapid deployment is important not just for reaching international climate change goals but also for putting aviation, a growing source of hard-to-abate RF, on a more sustainable trajectory.

In a world linked by global commerce and global environmental problems, aviation presents a special concern for the transition to a net-zero future. Recent experience suggests that commercial air traffic will continue to grow at a robust 5–7% per year[5][6]. By 2050, fuel use may increase GHG emissions by 2–4 times[7]. Given that skies over Europe and the US East Coast can already reach 10% contrail coverage annually[8], the RF from contrails may exhibit similar patterns of growth[9]. These non-GHG sources of aviation-related global warming are a substantial and growing threat to climate change mitigation.

Failing to address contrail formation threatens international climate change goals over the coming decades. While aviation contributed to 4% of total global anthropogenic RF in 2011[10], policymakers apprehend that ignoring these growing climate change drivers could undermine economy-wide mitigation efforts[11]. Modeling by Brazzola *et alia*[12] finds that even with GHG-neutral technologies and policies, non-CO_2 aviation RF has the potential to cause up to 0.4 °C of additional warming,

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[1] Lee et al., "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018."

[2] Meerkötter et al., "Radiative Forcing by Contrails."

[3] Lee et al., "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018."

[4] P Jaramillo and Kahn Ribeiro, S, "Chapter 10."

[5] Lim, Gardi, and Sabatini, "Optimal Aircraft Trajectories to Minimize the Radiative Impact of Contrails and CO2."

[6] Wilkerson et al., "Analysis of Emission Data from Global Commercial Aviation."

[7] Kärcher, "Formation and Radiative Forcing of Contrail Cirrus."

[8] Burkhardt and Kärcher, "Global Radiative Forcing from Contrail Cirrus."

[9] Kärcher, "Formation and Radiative Forcing of Contrail Cirrus."

[10] Kärcher.

[11] Lee et al., "Aviation and Global Climate Change in the 21st Century."

[12] Brazzola, Patt, and Wohland, "Definitions and Implications of Climate-Neutral Aviation."

making the Paris Climate Change Agreement's 1.5°C target impossible to reach. Mitigation of contrail formation provides essential long-term climate stability.

Policymakers and stakeholders from the aviation industry acknowledge the critical need for adopting contrail avoidance in their standard operations. Most visibly, late 2022 saw the formation of the Contrail Impact Task Force, consisting of five airlines (Alaska Airlines, American Airlines, Southwest Airlines, United Airlines, and Virgin Atlantic), two aircraft manufacturers (Airbus and Boeing), two information technology companies (Flightkeys and Google Research), Breakthrough Energy, RMI, and Imperial College London[13]. The Task Force seeks to collaborate on understanding contrail formation and developing strategies for enduring mitigation. By 2023, Google Research, Breakthrough Energy, and American Airlines demonstrated the effectiveness and low costs of diversion technologies, pointing the way to scalable solutions for further deployment[14]. Even as these technologies mature, though, the industry needs further characterizations of physical parameters about the climate implications of the diversion decision.

1.2 Gap Analysis

Research on the impact of contrail avoidance has picked up in recent years. Teoh, Schumann, and Stettler especially have looked at the impact of small-scale diversions on fuel consumption and air-traffic management in Japanese airspace[15]. Avila *et alia* performed similar analyses for flights over the United States[16]. These studies use a large amount of flight and meteorological data, as well as complex contrail models, such as the Contrail Cirrus Prediction Model (CoCiP) or algorithmic climate change functions (aCFFs), but only assess the impact of diversion with a single equivalence metric. Roosenbrand, Sun, and Hoekstra devised a global altitude diversion strategy to halve contrail impact while accounting for safety concerns and additional CO_2 emissions[17]. Dahlmann *et alia* proposed a simple calculation method to assess non-CO_2 impacts of flights using only flight distance and geographic flight region[18]. We have chosen to use a simple, hypothetical flight and focus on how the impact and consequently the decision to divert or not changes when different metrics are used.

This approach echoes previous studies on the impact of metric design on assessments of using natural gas as shipping fuel vs. using alternative fuels[19]. These studies focused on methane and showed that the value of alternative technologies varied substantially depending on which metric is used to assess it. We aim to do the same for contrail diversion. Different studies on contrails use

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[13] Cathcart and Chen, "Contrail Mitigation: A Collaborative Approach in the Face of Uncertainty."

[14] Elkin and Sanekommu, "How AI Is Helping Airlines Mitigate the Climate Impact of Contrails."

[15] Teoh et al., "Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption"; Teoh et al., "Aviation Contrail Climate Effects in the North Atlantic from 2016 to 2021"; Teoh et al., "Global Aviation Contrail Climate Effects from 2019 to 2021"; Frias et al., "Feasibility of Contrail Avoidance in a Commercial Flight Planning System"; Teoh, Schumann, and Stettler, "Beyond Contrail Avoidance."

[16] Avila, Sherry, and Thompson, "Reducing Global Warming by Airline Contrail Avoidance."

[17] Roosenbrand, Sun, and Hoekstra, "Contrail Minimization through Altitude Diversions."

[18] Dahlmann et al., "Climate Assessment of Single Flights."

[19] Balcombe et al., "Methane Emissions"; Edwards and Trancik, "Climate Impacts of Energy Technologies Depend on Emissions Timing."

different metrics and this lack of consensus has been already identified as a factor making the assessment of CO_2 and non-CO_2 impacts more complicated[20].

1.3 Objective

Mitigating the climate impacts of aviation requires creating a decision rule for whether or not to deviate the flight paths of individual aircraft for contrail avoidance. This study helps to fashion such a rule in two ways. The first objective is to assist aviation stakeholders in making an informed choice about which climate change equivalence metrics to use when assessing contrail climate impacts. The second objective is to propose a decision framework for contrail avoidance.

Climate change metrics are intended to measure the impacts of different climate forcing agents on a common scale, allowing for comparisons in the same units. In the dilemma presented here, decisionmakers must be able to compare the consequences of burning additional fuel to deviate a flight, and thus emitting GHGs, against the expected warming effects of creating contrail-cirrus. This tradeoff is complicated by the vastly different spatial and temporal scales of each climate forcing agent. Climate scientists have developed a wide, perhaps befuddling, variety of options. We provide an overview of current metrics, discuss the trade-offs between them, and explain how to choose among them, given the needs of stakeholders.

Weighing the costs and benefits of contrail avoidance requires a framework for properly accounting for all relevant variables and the subjective priorities of stakeholders. We provide such a framework and illustrate how it can be used with a case study for a specific flight. Real-world data reveal how the decision on whether to divert this flight to avoid forming a contrail is based on the contrail's potential climate impact.

2. Background

Guiding decisions around contrails requires a deeper understanding of their formation, climate impacts, and mitigation costs. This section provides an overview of these subjects, starting with an introduction to radiative forcing and its importance to global warming. While radiative forcing is fundamental to the climate change impacts of both GHG and contrails, a variety of more advanced and complex metrics serve different needs for comparing these drivers. Because mitigating contrails entails a trade-off between contrail formation and GHG emissions, it is important to use the appropriate metric to place these drivers on a common scale. Together, these explanations provide a foundation for our subsequent analyses in this study.

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[20] Teoh et al., "Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption."

2.1 Measuring Global Warming

Fundamentally, 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 our planet radiates as much energy back into space as it absorbs[21]. Since the Industrial Revolution, however, humans have altered this equilibrium, introducing drivers, especially GHG emissions, that increase energy absorption[22]. RF is therefore expressed as the difference in the energy balance between present day and pre-industrial times – typically 1750 – in energy per area, *e.g.*, watts per square meter[23].

RF is usually reported as an average over the Earth's surface to reflect a well-mixed pool of gases, but it is possible to estimate local RF for smaller geographic regions[24]. Scientists estimate RF at the top of the atmosphere. When a forcing agent is emitted, the change in net energy sets in motion a series of adjustment processes throughout the climate system[25]. 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[26]. All emission metrics use RF estimates as inputs into reduced-complexity climate models or in equations derived from more complex models[27].

Adding complexity to RF allows researchers to account for relevant real-world effects. A climate forcer can have a variety of knock-on effects on different parts of the climate system, such as 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 radiation back to the surface. To capture rapid adjustments in the climate system, the metric 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[28]. This ability makes ERF a better predictor of eventual climate responses, *e.g.*, temperature change, especially for forcing agents whose effect plays out largely through their effects on clouds, such as aerosols and contrails[29].

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[21] Trenberth, Fasullo, and Kiehl, "Earth's Global Energy Budget."

[22] Intergovernmental Panel On Climate Change, *Climate Change 2021 – The Physical Science Basis.*

[23] Bellouin, "AEROSOLS | Role in Climate Change."

[24] Teoh et al., "Aviation Contrail Climate Effects in the North Atlantic from 2016 to 2021"; Teoh et al., "Global Aviation Contrail Climate Effects from 2019 to 2021."

[25] Intergovernmental Panel On Climate Change, *Climate Change 2021 – The Physical Science Basis.*

[26] Myhre, Shindell, and Pongratz, "Anthropogenic and Natural Radiative Forcing."

[27] Intergovernmental Panel On Climate Change, *Climate Change 2021 – The Physical Science Basis.*

[28] Intergovernmental Panel On Climate Change.

[29] Bellouin, "AEROSOLS | Role in Climate Change."

ERF requires more complex modeling, as researchers must account for interactions between different forcing agents in the troposphere, not all of which are well understood[30]. Since its Fifth Assessment Report, the IPCC has started reporting ERF instead of RF values, primarily because ERF is a better predictor of temperature change, especially for aerosols[31]. This change in IPCC policy has put renewed focus on improving modeling of – and improving confidence in – ERF estimates in recent years. The Sixth Assessment Report revised many ERF estimates[32].

The main difference between RF, ERF, and other, less-common sub-definitions of RF is whether the accounting for a climate forcer's impacts on temperature include simply direct effects or also indirect effects, as through climate feedback. When immediate effects and longer-term feedback, like cloud adjustments, counteract, these metrics can differ significantly for certain forcers[33].

2.2 Contrail Formation, Impact, and Mitigation

Contrails form when hot exhaust gases and water vapor from the jet engine mix with the surrounding atmosphere. The thin contrail that can be observed in the sky does not persist for longer than a few minutes, but in cold and humid atmospheric regions, so-called "ice supersaturated regions" (ISSRs), thin contrails have the potential to persist for longer periods of time and expand into cirrus clouds[34]. These cirrus clouds contribute to the greenhouse effect in the same way that natural clouds do. During the day, contrails cool the Earth roughly as much as they warm it by reflecting some incoming shortwave radiation from the Sun and trapping in outgoing longwave radiation. However, during the night, there is no shortwave radiation to reflect and so, on average, contrails warm our atmosphere[35]. Overall, contrails are thought to make up around two thirds of the total forcing caused by aviation, although uncertainties in contrail RF measurement persist [36].

The values of RF for contrails are unevenly distributed between flights because the time of day and geographic region matter greatly for the contrail climate impact. In the North Atlantic, 12% of flights cause around 80% of annual forcing from contrails[37]. Persistent contrails formed in ISSRs make up the bulk of this warming, and so avoiding ISSRs by adapting flight altitude has the potential to mitigate contrail warming, as illustrated in Figure 1. Teoh et al.[38] showed that annual contrail forcing over Japanese airspace could be reduced by around 60% by diverting only 2% of flights, with minimal impact on air traffic management. Altitude changes like the ±2000 feet deviation proposed in Teoh *et alia*, however, lead to increased fuel use, *i.e.*, GHG emissions, increasing the flight's long-

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[30] Intergovernmental Panel On Climate Change, *Climate Change 2021 – The Physical Science Basis*.

[31] Myhre, Shindell, and Pongratz, "Anthropogenic and Natural Radiative Forcing."

[32] Intergovernmental Panel On Climate Change, *Climate Change 2021 – The Physical Science Basis*.

[33] Bellouin, "AEROSOLS | Role in Climate Change."

[34] Avila, Sherry, and Thompson, "A Contrail Inventory of U.S. Airspace (2015)."

[35] Teoh et al., "Aviation Contrail Climate Effects in the North Atlantic from 2016 to 2021."

[36] Lee et al., "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018."

[37] Teoh et al., "Aviation Contrail Climate Effects in the North Atlantic from 2016 to 2021."

[38] Teoh, Schumann, and Stettler, "Beyond Contrail Avoidance."

term climate impact. Climate metrics can help compare the long-term impacts of increased fuel use and the contrails in equivalent units.

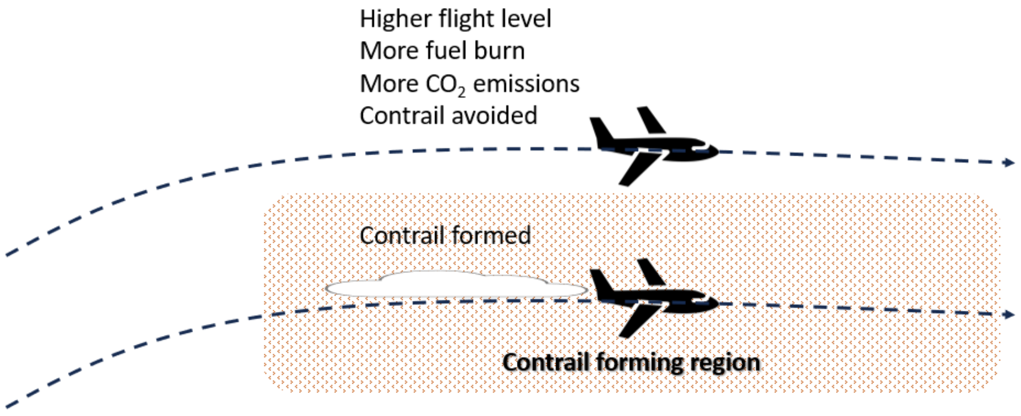

Figure 1. Increased flight level to avoid contrail forming region results in additional fuel burn and associated CO_2 emissions.

3. Contrail Mitigation Decisions and Climate Metrics

Mitigating the climate impacts of aviation requires creating a decision rule for whether or not to avoid creating contrails. Some flights can avoid creating contrails by diverting their paths, 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 below in Figure 2 illustrates the situation. If the contrail is cooling, then it should not be avoided. If the contrail 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.

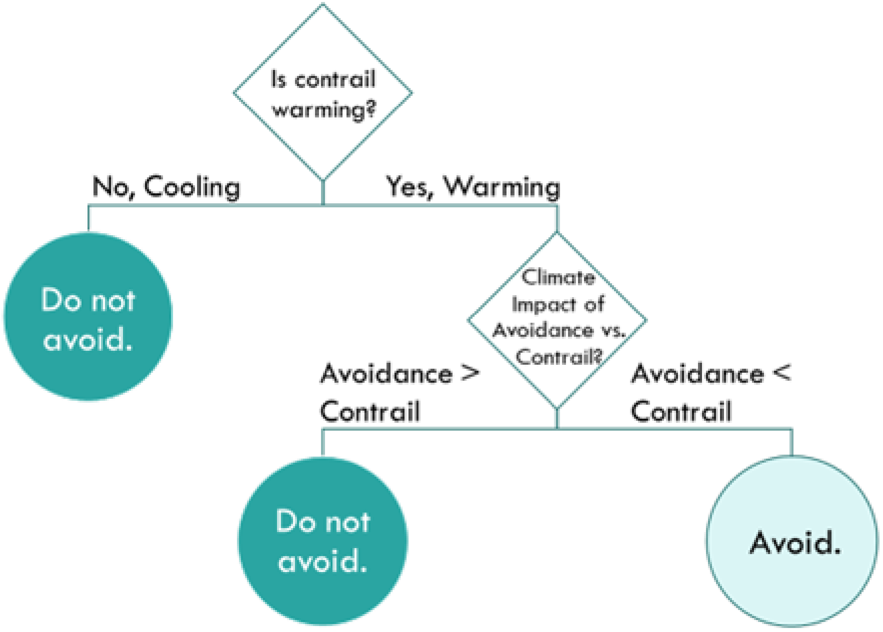

Figure 2. Basic contrail avoidance decision tree

It is important to take a 'Well-to-Wake' approach (Figure 3), capturing the embodied impacts of additional fuel production (Well-to-Pump, WTP) due to contrail avoidance and the additional combustion-related impacts (Pump-to-Wake, PTWa). *If the WTP phase is ignored, the impact of contrail avoidance will be underestimated.* For aviation-relevant short-lived climate forcers (SLCF, *viz.*, carbon monoxide, nitrogen oxides, 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 (e.g., [39]) should be applied to PTWa combustion emissions[40].

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[39] Lee et al., "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018."
[40] Miller, Chertow, and Hertwich, "Liquid Hydrogen."

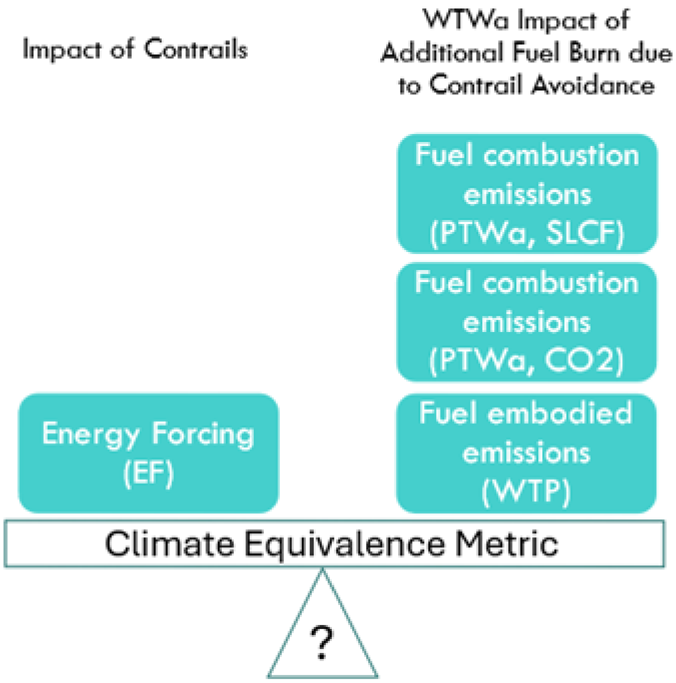

Figure 3. Applying climate equivalence metrics to determine the balance between the impact of contrails and the 'Well-to-Wake' (WTWa) impact of additional fuel burn due to contrail avoidance

This manuscript 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 carbon dioxide (CO_2) and non-CO_2 impacts[41]. The approach in this manuscript echoes previous studies on the impact of metric design on assessments of comparing natural gas and alternative shipping fuels[42]. These studies focused on methane and show that the value of alternative technologies varied substantially depending on the climate metric used to assess them.

Recently, Borella et al.[43] 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. They found, "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 (p. 13)."

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[41] Teoh et al., "Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption."

[42] Balcombe et al., "Methane Emissions"; Edwards and Trancik, "Climate Impacts of Energy Technologies Depend on Emissions Timing."

[43] Borella et al., "The Importance of an Informed Choice of CO2 Equivalence Metrics for Contrail Avoidance."

4. Climate Metrics for Contrails

A climate equivalency metric functions similarly to an exchange rate between two currencies. If someone received payments of 100 USD and 300 RMB, the total worth of those payments requires first convert to a common currency before taking a sum. An exchange rate provides a ratio between units of currency between two countries, 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 an emission of 1 kg of CO_2. By definition, the conversion factor for CO_2 is always 1 kg CO_2-eq per 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 Intergovernmental Panel on Climate Change (IPCC)[44], the climate impact of emitting 1 kg of nitrous oxide (N_2O) is equivalent to emitting 273 kg CO_2 using the 100-year time horizon Global Warming Potential (GWP100) metric, and thus its impact would be written as 273 kg CO_2-eq. 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-eq. Borella et al.[45] elected to use AGWP100 and Absolute Global Temperature Potential (AGTP100) directly, rather than making a comparison with CO_2.

$$GWP100_{N2O} = \frac{AGWP100_{N2O}}{AGWP100_{CO2}} = \frac{24.5\, pW\, m^{-2}\, yr\, kg_{N2O}^{-1}}{0.0895\, pW\, m^{-2}\, yr\, kg_{CO2}^{-1}} \approx 273\ \frac{kg_{CO2-eq.}}{kg_{N2O}}$$

$$GTP100_{N2O} = \frac{AGTP100_{N2O}}{AGTP100_{CO2}} = \frac{0.0919\, pK\, kg_{N2O}^{-1}}{0.000395\, pK\, kg_{CO2}^{-1}} \approx 233\ \frac{kg_{CO2-eq.}}{kg_{N2O}}$$

While GWP100 is the most common metric, there are a variety of climate equivalency metrics, each with a different approach to expressing the impact of an emission in CO_2-equivalent terms[46]. These metrics estimate various impacts, such as energy forcing, temperature change, precipitation, sea level rise, or even economic damage, caused by a climate forcer.

In this manuscript, we focus on metrics that deal with energy forcing and temperature change, shown in Table 1.

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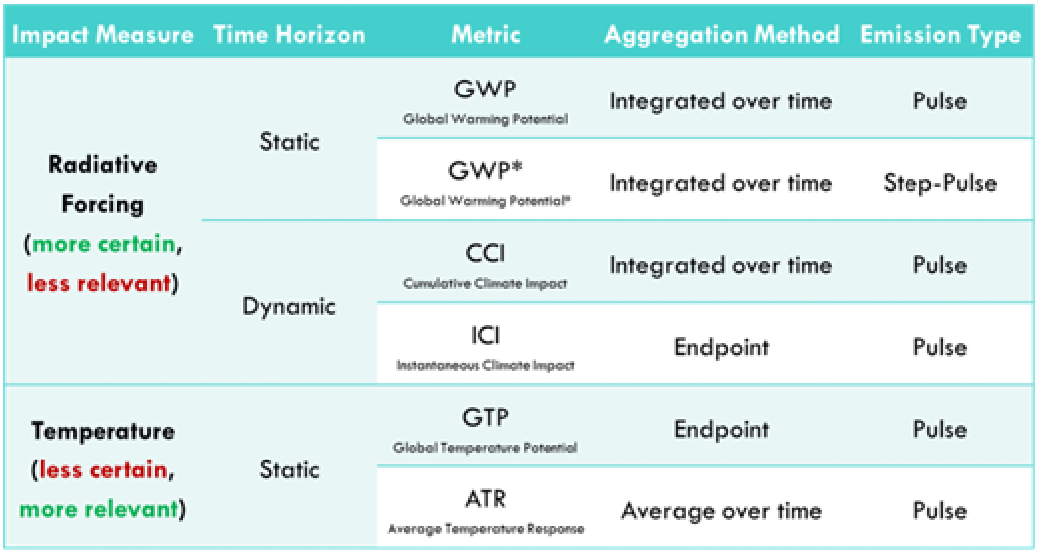
[44] Forster et al., "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity", Table 7.SM.7.
[45] Borella et al., "The Importance of an Informed Choice of CO2 Equivalence Metrics for Contrail Avoidance."
[46] Edwards and Trancik, "Consequences of Equivalency Metric Design for Energy Transitions and Climate Change."

Table 1. Key Attributes of Climate Equivalency Metrics



Impact Measure	Time Horizon	Metric	Aggregation Method	Emission 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

4.1 Impact Measures

Radiative Forcing (RF) measures the energy imbalance between pre-industrial times and a given year. RF at a target year is directly captured in the Instantaneous Climate Impact (ICI) metric. The metrics GWP, GWP*, and Cumulative Climate Impact (CCI) go one step further by integrating the RF over the time horizon. GTP and Average Temperature Response (ATR) measure the temperature impacts of emissions, instead of the total forcing, since *temperature* is the main driver of climatic impact and mentioned in international treaties.

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 Figure 4, 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. Effective Radiative Forcing (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. We do not consider RF or ERF at the time of flight as plausible metrics for the contrail avoidance decision, as they reflect a snapshot in time and do not consider impacts over time.

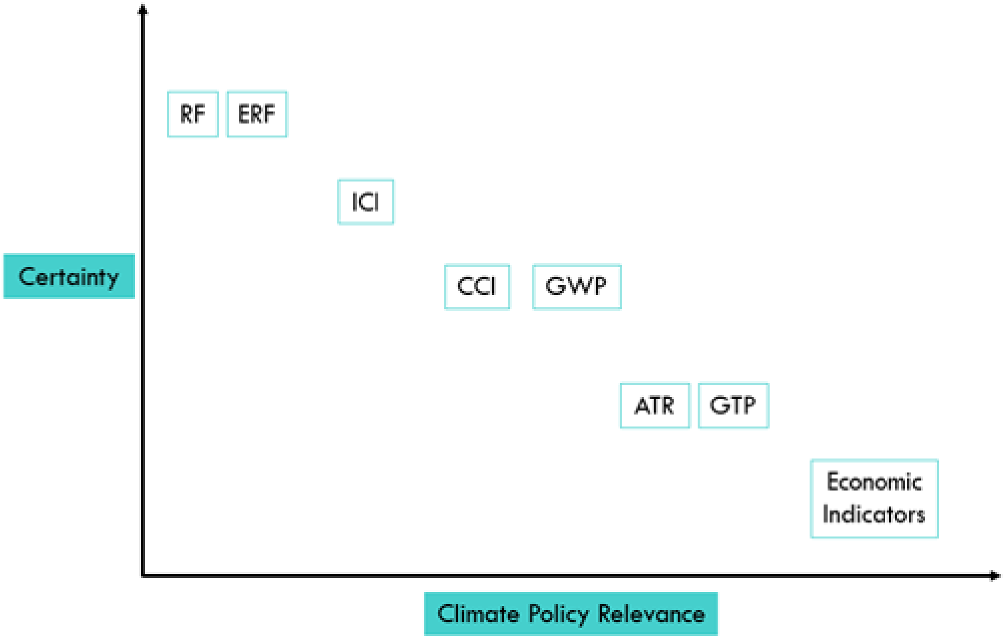


Figure 4. Tradeoff between certainty and relevance across climate equivalency metrics.

4.2 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. For the illustrative dynamic time horizons depicted in Figure 5, 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 the emission will be evaluated for the following 100 years, regardless of earlier climate targets.

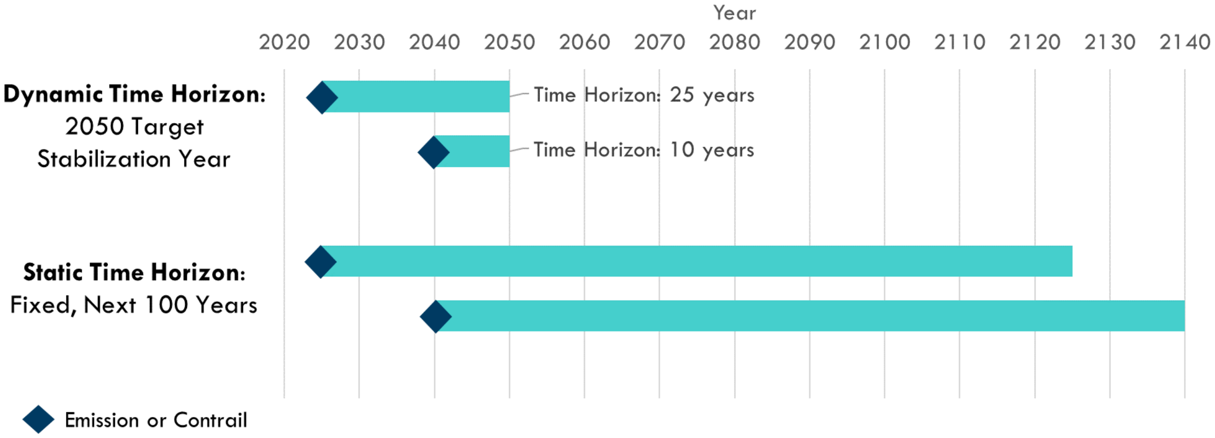


Figure 5. Illustrative Dynamic and Static Time Horizons

4.3 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.

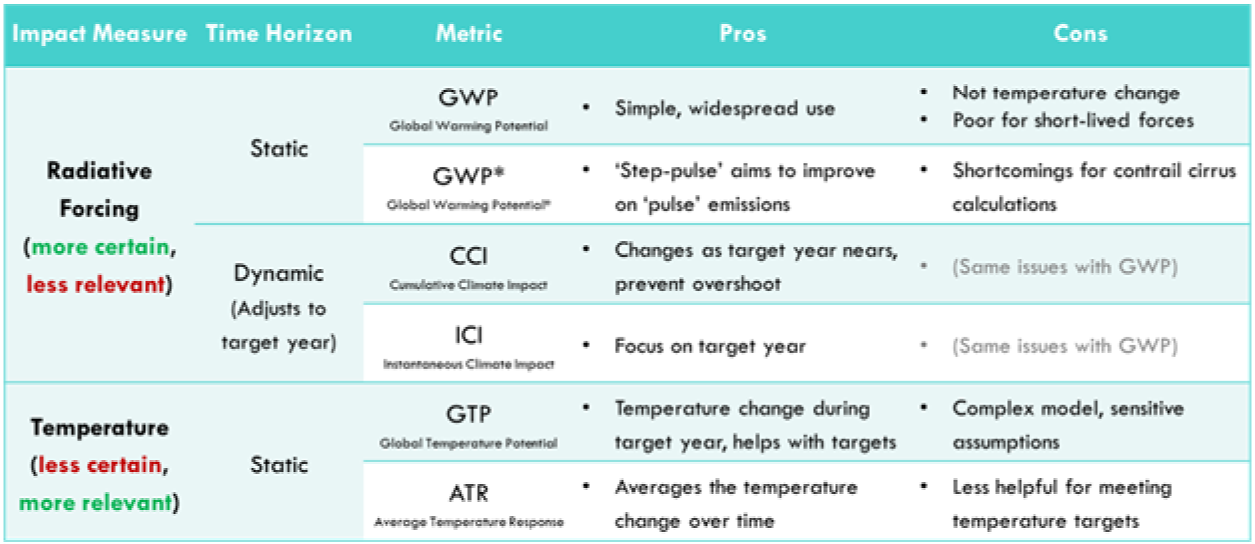
4.4 Emission Type

Models can also differ by whether they are using pulses or steps as their basic unit of emission. Most metrics model the effect of a *pulse* emission, 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 forcers with shorter atmospheric lifetimes (SLCFs), as emission rates could potentially be informative about the resulting stock of the forcer affecting the climate. We briefly discuss below why we follow other authors in excluding step-pulse metrics (*e.g.*, GWP*) for the purpose of estimating contrail impacts.

5. Evaluating climate metrics for decisionmaking

Table 2 summarizes the advantages and disadvantages of the various climate equivalency metrics discussed in this section.

Table 2. 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 Poor for short-lived forces
		GWP* Global Warming Potential*	'Step-pulse' aims to improve on 'pulse' emissions	Shortcomings for contrail cirrus calculations
	Dynamic (Adjusts to target year)	CCI Cumulative Climate Impact	Changes as target year nears, prevent overshoot	(Same issues with GWP)
		ICI Instantaneous Climate Impact	Focus 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

5.1. Global Warming Potential (GWP)

Global Warming Potential is the primary climate metric – alongside Global Temperature Change Potential (GTP) – reported by the IPCC (see [[47]]). Somewhat confusingly, however, it is not a measure of warming or temperature change but of the total energy trapped in the Earth 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[48]. 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.

5.1.1 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 emerged, the costs and dangers of re-writing international climate treaties would be immense[49]. Private firms and governments reciprocally expect each other to report GHG emissions using GWP100 values, the common language that allows comparisons between gases, 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.

5.1.2 GWP – Cons

Objections to GWP begin with the very nomenclature of the metric. Indeed, the naïve interpretation is far removed from its real meaning[50]. The quantity that GWP measures, *i.e.*, 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[51]. The sum of incoming radiation which 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 SLCFs (including contrails) are meaningless beyond a certain time horizon. For example, after 40 years, more than 95% of the methane from an emission

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[47] Forster et al., "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity."

[48] "IPCC Expert Meeting on the Science of Alternative Metrics."

[49] Schleussner et al., "Inconsistencies When Applying Novel Metrics for Emissions Accounting to the Paris Agreement."

[50] Shine, "The Global Warming Potential—the Need for an Interdisciplinary Retrial."

[51] Trenberth, Fasullo, and Kiehl, "Earth's Global Energy Budget."

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 AGWP value for CO_2 in the denominator of the calculation[52]. 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 CO_2-equivalents continue to rise[53]. In the context of multi-gas treaties like the Kyoto Protocol and the Paris Climate Change 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[54]. Many of these scenarios lie beyond the stated temperature goals of either agreement.

5.2 Global Warming Potential* (GWP*)

GWP* is a step-pulse metrics which tries to remedy a common criticism of integrated metrics such as GWP. While we mention it here, we will not be actively considering it, as we think it is not useful in the context of contrail mitigation. Almost all the criticisms laid out in Meinshausen and Nicholls[55] for GWP* in general also apply to contrails. Please refer to their paper for a more detailed explanation as to why GWP* is ill-suited as a metric in operational contexts.

5.3 Cumulative Climate Impact (CCI) and Instantaneous Climate Impact (ICI)

Edwards and Trancik[56] proposed two dynamic metrics, the Cumulative Climate Impact (CCI) and Instantaneous Climate Impact (ICI). 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, as illustrated in Figure 4.3 above. ICI is the radiative forcing of the climate forcer in the target year.

5.3.1 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

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[52] Kleinberg, "The Global Warming Potential Misrepresents the Physics of Global Warming Thereby Misleading Policy Makers."

[53] Forster et al., "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity."

[54] Dhakal et al., "Emissions Trends and Drivers"; Fuglestvedt et al., "Transport Impacts on Atmosphere and Climate."

[55] Meinshausen and Nicholls, "GWP*is a Model, Not a Metric."

[56] Edwards and Trancik, "Climate Impacts of Energy Technologies Depend on Emissions Timing."

stabilization year[57]. 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[58]. 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.

5.3.2 CCI and ICI – Cons

The main issue for using CCI or ICI is making the metric comparable across different users. Users must agree on a 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 also pose issues in later years.

5.4 Global Temperature Potential (GTP)

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 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 CO2. Since GTP only reports the temperature change in Kelvin (K) 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[59]. 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[60]. The 90% confidence interval for the GTP of methane, for example, spans ±40% of the GWP value, whereas the interval for GTP is ±70%[61].

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[57] Edwards and Trancik.

[58] Edwards and Trancik, "Consequences of Equivalency Metric Design for Energy Transitions and Climate Change."

[59] Yoshimori et al., "A Review of Progress towards Understanding the Transient Global Mean Surface Temperature Response to Radiative Perturbation."

[60] Fuglestvedt et al., "Transport Impacts on Atmosphere and Climate."

[61] Balcombe et al., "Methane Emissions."

5.4.1 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 radiative forcing, 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[62].

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[63]. Nevertheless, GTP is a reasonable middle ground between sophisticated temperature tracking and relatively low computational complexity. More complex climate models, while more accurate, are computationally too expensive for day-to-day 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[64]. 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[65].

5.4.2 GTP – Cons

The major disadvantage of GTP is the inherent uncertainty in its estimates of CO_2-equivalence. 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[66].

While the differences between theoretical and realized warming trajectories using CO_2-equivalent GTP values are significantly smaller than when using GWP, there is still uncertainty in warming pathways before and after the target year, as GTP's endpoint design leaves us unable to assess impacts outside out the chosen endpoint[67]. For example, a scenario with a large amount of short-

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[62] "IPCC Expert Meeting on the Science of Alternative Metrics."

[63] Kleinberg, "The Global Warming Potential Misrepresents the Physics of Global Warming Thereby Misleading Policy Makers."

[64] Fuglestvedt et al., "Transport Impacts on Atmosphere and Climate."

[65] "IPCC Expert Meeting on the Science of Alternative Metrics."

[66] Myhre, Shindell, and Pongratz, "Anthropogenic and Natural Radiative Forcing."

[67] Koch, "Climate Impact Mitigation Potential given by Flight Profile and Aircraft Optimization."

lived emissions could lead to warming levels above the stabilization temperature predicted by GTP in the years before the endpoint, which could potentially have unforeseen consequences.

5.5 Average Temperature Response (ATR)

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)[68]. While it was originally designed to assess the impact of aircraft designs, it is now used both in fleet and single flights assessments[69]. 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[70]. 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[71].

5.5.1 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[72]. There is thus less uncertainty in the exact warming pathway than when using GTP.

5.5.2 ATR – Cons

If the primary aim of comparing climate forcers is to keep temperatures under a certain threshold, such as those of the Paris 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 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[73].

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[68] Dahlmann et al., "Can We Reliably Assess Climate Mitigation Options for Air Traffic Scenarios despite Large Uncertainties in Atmospheric Processes?"

[69] Dallara, Kroo, and Waitz, "Metric for Comparing Lifetime Average Climate Impact of Aircraft"; Dahlmann et al., "Climate Assessment of Single Flights."

[70] Dahlmann et al., "Can We Reliably Assess Climate Mitigation Options for Air Traffic Scenarios despite Large Uncertainties in Atmospheric Processes?"

[71] Koch, "Climate Impact Mitigation Potential given by Flight Profile and Aircraft Optimization."

[72] Koch.

[73] Dallara, Kroo, and Waitz, "Metric for Comparing Lifetime Average Climate Impact of Aircraft."

6. 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* a time period, while 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 tradeoffs between short- and long-term strategies. GHG emissions and contrails contrast in two major regards: duration and ease of mitigation. Some GHGs remain in the atmosphere for millennia, others only for a few hours. Some contrails dissipate rapidly, while 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[74]. Some GHGs are evenly distributed throughout our atmosphere, while contrails and other GHGs 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 by Houghton et al.[75] 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 a more careful consideration. The 1997 Kyoto Protocol used GWP100 – not based on careful consideration but, instead and most likely, as a compromise, since it constituted the middle value of the three time horizons proposed in 1990[76].

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 short-lived forcers to CO_2. Many non-CO_2 gases 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 gases dissipate on a much shorter timescale, after which they do not impact the climate. Therefore, a short time horizon like 20 years will tend to assign a stronger weight to short-lived GHGs, 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 end-point metrics, which only assess the impact at the end of the chosen horizon. Borella et al.[77] 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. (p. 16)"

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[74] Borella et al., "The Importance of an Informed Choice of CO2 Equivalence Metrics for Contrail Avoidance."

[75] Houghton, Jenkins, and Ephraums, *Climate Change: The IPCC Scientific Assessment.*

[76] Myhre, Shindell, and Pongratz, "Anthropogenic and Natural Radiative Forcing."

[77] Borella et al., "The Importance of an Informed Choice of CO2 Equivalence Metrics for Contrail Avoidance."

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.

6.1 Physical approach for determining time horizons

The physical approach uses **climate targets** as the anchors from which the appropriate time horizons can be calculated. Abernethy and Jackson[78], for example, have calculated the time horizons corresponding to the temperature targets in the Paris Climate Change Agreement. They use our 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 is 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 we approach a target year. 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 our goals and needs.

6.2 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 Sarofim and Giordano[79] have estimated to imply time horizons of 118 years and 38 years, respectively. An in-depth discussion of appropriate choices for discount rates is fraught with normative assumptions, and so is beyond the scope of this chapter.

7. Selection of climate impact metric(s)

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 or not to avoid contrail creation, it's important to adopt a climate equivalency metric and time horizon that satisfy predetermined criteria. Borella et al.[80] offer a more detailed discussion of the potential implications of selecting the various metrics in their simulation of

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[78] Abernethy and Jackson, "Global Temperature Goals Should Determine the Time Horizons for Greenhouse Gas Emission Metrics."

[79] Sarofim and Giordano, "A Quantitative Approach to Evaluating the GWP Timescale through Implicit Discount Rates."

[80] Borella et al., "The Importance of an Informed Choice of CO2 Equivalence Metrics for Contrail Avoidance."

the North Atlantic. Summarizing their conclusions in this chapter, the criteria for a climate metric should consider preferences for 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 (end point); and
- static time horizon of length 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 formula, following [81]:

$$\frac{Contrail_{GWP,H}[kg\ CO2e]}{Contrail_{EF}[J]} = \frac{\frac{ERF}{RF}}{time\ per\ year[s] \times Earth's\ surface\ [m^2] \times AGWP_{H,\,CO2}[\frac{Wm^{-2}}{kgCO2}]}$$

Climate scientists must overcome the current challenge of constructing an efficient means for accurately converting contrail energy forcing (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, a variety of 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 et al.[82] 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. (p. 17)"

8. Contrail Decision Matrix

To aid the operational decision-making process, we created a spreadsheet showing a matrix of the impacts of contrail energy forcing along the vertical axis and additional fuel burn due to additional contrail avoidance along the horizontal axis. The values along the vertical axis are based on the estimated 2019 percentiles of energy forcing (EF)[83] and are grouped into a new concept: the **Contrail Severity Index**, which categorizes warming EF into groups of low, medium, and high. The percentages of additional fuel burn values along the horizontal axis grow in increments of 5 or 10 times (*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[84] aircraft type used to approximate the default fuel burn (kg fuel / km flight distance). At the time of publication,

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[81] Frias et al., "Feasibility of Contrail Avoidance in a Commercial Flight Planning System."

[82] Borella et al., "The Importance of an Informed Choice of CO2 Equivalence Metrics for Contrail Avoidance."

[83] Breakthrough Energy, "Energy Forcing Interpretation."

[84] Wang et al., "Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model ® (2023 Excel)."

the matrix is available for GWP20 and GWP100, but future efforts could develop additional climate equivalency metrics. We used custom inputs in place of the default values of four variables:

- ratio between contrail ERF / RF, default: 0.42 from [[85]]
- fuel burn (based on GREET1 2023)
- WTWa impact of additional fuel burn, calculated from [[86]]:
    - 12.66 kg CO2e/kg fuel for GWP20
    - 5.20 kg CO2e/kg fuel for GWP100
- AGWP$_{CO2}$, from [[87]]:
    - 2.43E-14 Wm^{-2}yr kg CO2^{-1} for AGWP20
    - 8.95E-14 Wm^{-2}yr kg CO2^{-1} for AGWP100.

After making the choice above, to use the matrix, first locate the row which reflects the estimated EF per flight distance of the expected contrail from the flight. Next, locate the column which 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.

Figure 6 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 Figure 2. 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. The areas where decisions must be made around diversion in these cases 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 here 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. If there are solely positive or negative values in that region, the decision is clear. If there are 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

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[85] Lee et al., "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018."

[86] Wang et al., "Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model ® (2023 Excel)"; Lee et al., "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018."

[87] Forster et al., "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity", Table 7.SM.7.

assumption of precision and accuracy. Miller et al.[88] demonstrated the use of Monte Carlo simulations for this purpose in their comparative life cycle assessment of hydrogen jet fuels, following a method described by Gregory et al.[89].

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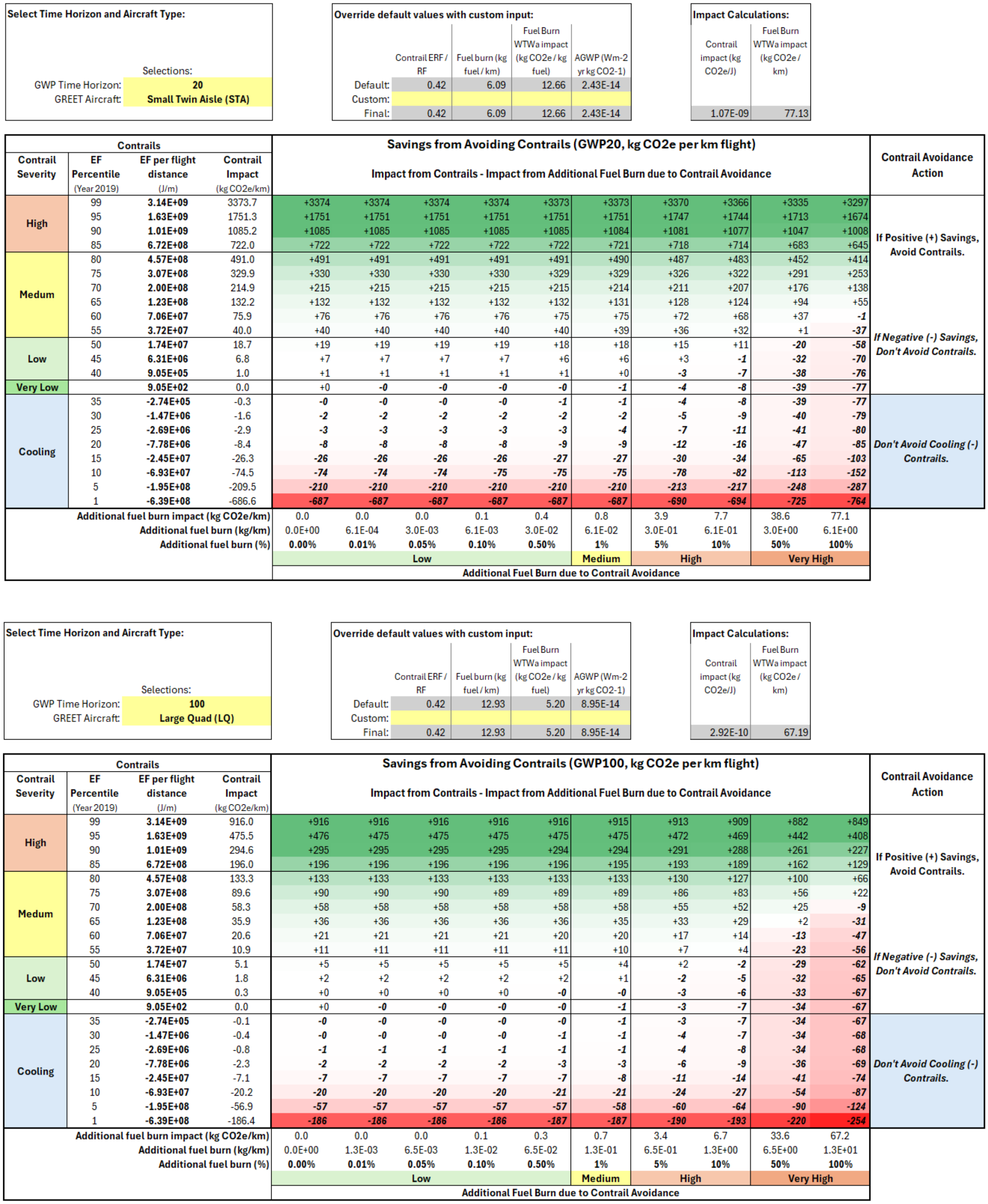
[88] Miller, Chertow, and Hertwich, "Liquid Hydrogen."

[89] Gregory et al., "A Methodology for Robust Comparative Life Cycle Assessments Incorporating Uncertainty."



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	If Positive (+) Savings, Avoid Contrails.
	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	
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	If Negative (-) Savings, Don't Avoid Contrails.
Low	50	1.74E+07	18.7	+19	+19	+19	+19	+18	+18	+15	+11	-20	-58	
	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	Don't Avoid Cooling (-) Contrails.
	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	
	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	If Positive (+) Savings, Avoid Contrails.
	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	
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	If Negative (-) Savings, Don't Avoid Contrails.
Low	50	1.74E+07	5.1	+5	+5	+5	+5	+5	+4	+2	-2	-29	-62	
	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	Don't Avoid Cooling (-) Contrails.
	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	
	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										

Figure 6. Decision matrix for contrail avoidance. If savings are positive, contrails should be avoided; if negative, they should not be. Upper: GWP20 and Small Twin Aisle aircraft. Lower: GWP100 and a Large Quad aircraft.

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