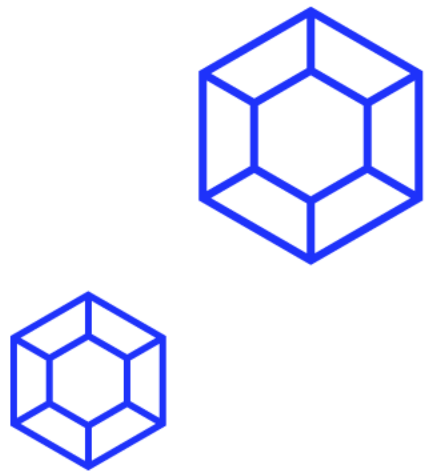
IN-DEPTH

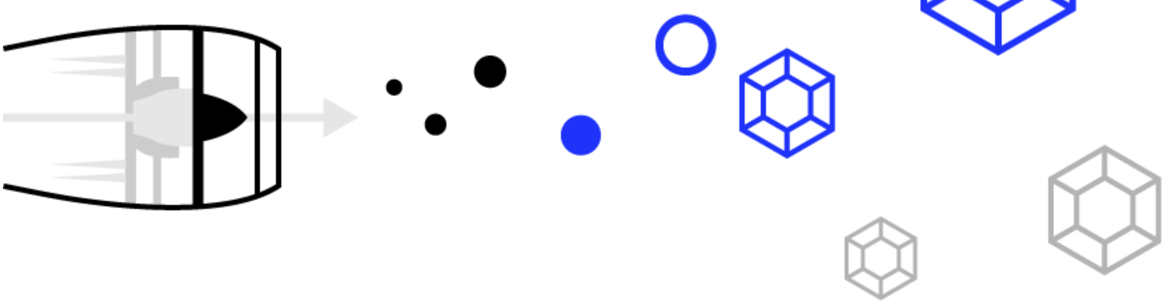
The non-CO2 climate co-benefit of SAF and other fuels with low aromatic and sulfur content

Current scientific knowledge and challenges

May 2025

Air transportation's non-CO2 emissions contribute to climate warming, with contrail-cirrus playing a major role. Reducing soot emissions via Sustainable Aviation Fuel (SAF) or low-naphthalene low-sulfur jet fuel can mitigate contrail impacts. However, uncertainties remain, especially in low-soot conditions where other emissions may contribute more to ice crystal formation. Strategic mitigation, such as using SAF on high-impact routes or optimizing Conventional Aviation Fuel (CAF) properties, could maximize benefits in the short term. Nonetheless, the economic and environmental trade-offs, as well as safety and infrastructural challenges, should be better assessed to determine feasible solutions. A collaborative, industry-wide approach is needed to balance environmental goals with economic and technological realities.





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Executive summary

Air transport's total environmental impact results from both its CO_2 and non-CO_2 emissions (e.g., NO_x and contrails). Non-CO_2 effects have a global warming impact that has been estimated to comprise approximately half of the industry's total climate impact, albeit with a much wider range of uncertainty in the precise quantification compared to that of CO_2. Non-CO_2 effects are also short-lived (i.e., hours to decades) compared to CO_2 emissions which accumulate in the atmosphere for hundreds of years.

SAF is one of the main decarbonization levers for the air transport industry. According to IATA's Net Zero Roadmap, almost two-thirds of the industry's sector-wide CO_2 emission abatement will be achieved by using SAF. While technologies for producing SAF are well understood, and the HEFA pathway in particular is commercially mature, supply is likely to be limited in the near future. However, increased SAF production and adoption would not only cut CO_2 net emissions, but the use of SAF can also bring non-CO_2 climate and air quality co-benefits by reducing particle emissions. While the air transport industry's priority should remain the reduction in CO_2 emissions because of their long-term cumulative warming effect, and because the science is more certain in this domain, the industry should also capitalize on the non-CO_2 co-benefits of SAF to achieve and maximize its environmental benefits and reduce the industry's environmental impact further. This approach would minimize the total environmental near-term impact while allowing time for fully sustainable solutions to develop, which can address non-CO_2 climate drivers such as contrails.

Numerous measurement studies have shown that jet engines burning SAF or fuels with lower aromatic and sulfur content modify aircraft engine emissions compared to conventional fossil-based jet fuel (CAF). Specifically, emissions of black carbon, or "soot", and smaller particles such as those derived from sulfur dioxide are curtailed. Based on these studies, it is widely accepted that SAF and other fuels with these properties exhibit lower soot emissions in comparison with CAF and that a large fraction of the soot emissions is from naphthalene compounds.

Contrail cirrus clouds have a significant warming effect on the climate. Most of today's jet engines emit large amounts of soot particles, which contribute to the formation of the ice crystals that make up contrails and impact the climate. In this high-soot regime, measurement and modeling studies have shown that reducing soot emissions by using SAF with lower naphthalenes and sulfur content can have a positive contrail climate benefit.

Modern jet engines with newer technologies (e.g., TAPS combustors), or older engines burning fuel with near-zero levels of naphthalenes or sulfur, emit considerably fewer soot particles. However, the smaller particles emitted from the engine or entrained from the ambient atmosphere in this low-soot regime can also contribute to the formation of ice crystals. Ambient conditions, such as temperature and humidity, can potentially increase the radiative and climate impact of the contrail. While more measurements and research are needed to better understand the role of these smaller particles in contrail formation, recent studies indicate the importance of reducing both soot and smaller particles from engine emissions to achieve climate and air quality benefits.

The climate impact of contrails is short-lived and dependent on the geographical location, altitude, and time of day and year in which they form and persist. Studies have found that only a small number of flights are responsible for most of the contrail climate warming. Given that scaling up SAF production is slow and that supplies are limited, prioritizing SAF use on specific routes that are more prone to forming highly warming contrails could be an efficient strategy to optimize the climate co-benefits of SAF in the shorter term. However, there are significant and costly logistical and infrastructural issues and challenges that need to be addressed in determining the feasibility of such strategies.

Altering fuel composition by removing or reducing naphthalenes and sulfur from CAF to reduce particle emissions is also being considered as a strategy to help reduce air transportation's non-CO_2 impacts. While current refining technologies to optimize fuel composition for environmental benefits exist, producers and suppliers have little incentive given the associated added costs. In addition, the extra processing required will lead to increases in the life cycle emissions, resulting in a climate penalty. Modifying fuel standards may be a way to mitigate non-CO_2 effects, but in-depth comprehensive assessments of the associated safety, economic, technological, and environmental trade-offs are required to determine optimal and feasible solutions, including policy incentives, before any further decisions are made.

Mitigating non-CO_2 effects is complicated by complex interdependencies and trade-offs, as well as scientific uncertainties associated with some of the related processes. An industry-wide approach built on multi-stakeholder and scientific collaboration is needed to find achievable smart solutions. These solutions should also consider environmental and technological changes over the next couple of decades. Changes in the background state of the atmosphere due to reductions in surface emissions from other sectors, as well as changes in the climate, will have an influence on the effects of non-CO_2 emissions. Furthermore, with fleet turnover, low soot-producing engines will eventually replace the non-CO_2 benefits of fuel with lower aromatic content.

1. Introduction

The use of sustainable aviation fuels (SAF) can significantly reduce life cycle carbon dioxide (CO_2) emissions when compared to the use of conventional aviation fuel (CAF). SAF are defined as jet fuel derived from biomass or non-biomass waste that has been certifiably produced in conformity with aviation fuel quality specifications and sustainability criteria, considering both carbon and environmental factors. Specifically, SAF refers to the synthetic blend component (SBC) produced from sustainable feedstock that needs to be blended with CAF to meet specifications for use in an aircraft.

From the several solutions identified to support the aviation industry's pledge to achieve net zero CO_2 emissions by 2050, the use of SAF is the lever that will contribute the most in terms of CO_2 lifecycle emission reductions.[1]

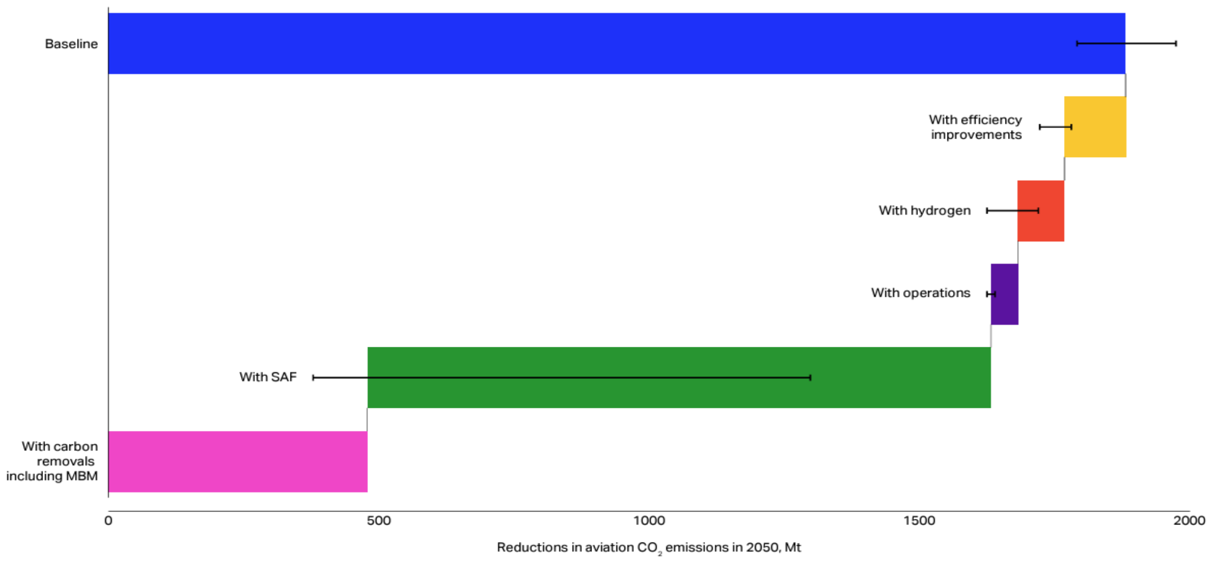
In 2021, a resolution was passed by IATA member airlines setting the goal to achieve net-zero carbon emissions from their operations by 2050, representing the first ever industry to voluntarily commit itself to a decarbonization strategy of this nature. Reaching this target requires a comprehensive approach to emissions from aviation, including the following:

1. The production, scaling, and deployment of SAF.
2. The deployment of fuel-efficient aircraft, which will eventually include new airframe and propulsion systems.
3. Sector-wide efficiency improvements, especially in operations, including air traffic management, flight rerouting/optimized trajectories, and ground handling and taxiing.
4. Investments in high-quality and independently verified offsets, as well as carbon removal opportunities to address residual CO_2 emissions.

From the above measures, it is estimated that approximately 62% of the industry's sector-wide CO_2 emission abatement would be achieved by using SAF, thereby underpinning its status as the central driver of the sector's pledge.[2] The following figure illustrates these different levers and their potential contribution to lower CO_2 emissions from aviation according to the IATA Net Zero Roadmaps:

[1] https://www.iata.org/en/pressroom/2024-releases/2024-04-17-01/
[2] IATA, 6 June 2023: "SAF Production Set for Growth but Needs Policy Support to Diversify Sources," https://www.iata.org/en/pressroom/2023-releases/2023-06-06-01/

Figure 1: Levers of action for aviation CO_2 emissions reductions by 2050. The solid bar indicates the central case and the black lines indicate maximum and minimum reductions based on the scenarios modelled



Source: IATA Sustainability and Economics, ICAO LTAG SAF availability scenarios.

In addition to CO_2, aviation's non-CO_2 emissions have a global warming impact that has been estimated to comprise about two-thirds of the sector's total climate impact[3]. Due to the complex, non-linear and interdependent nature of the processes associated with non-CO_2 effects, there is a much wider range of uncertainty in the precise quantification of the net warming impact compared to that of CO_2. Nevertheless, the range of uncertainty that has been estimated is between half and three times the impact of CO_2 which is significant.

Potential mitigation measures fall into three categories,

1. Flight rerouting / optimized trajectories
2. Fuel optimization
3. New engine technologies

As a potential non-CO_2 mitigation measure, SAF can provide both non-CO_2 climate and local air quality (LAQ) benefits that the aviation industry could capitalize on to further reduce environmental impact. The use of SAF modifies aircraft engine particle emissions compared to CAF, specifically for non-volatile and volatile particulate matter (PM). SAF from biogenic feedstocks contain no or significantly lower aromatic and sulfur contents compared with CAF. Low or no aromatic and sulfur content help reduce the number and mass of emitted PM (Moore et al., 2017; Voigt et al., 2021; Jasiński et al., 2024). As a result, and based on numerous measurement studies, it is now widely accepted that SAF exhibit significantly lower soot emissions in comparison with CAF and that a large fraction of the soot emissions is from naphthalene compounds.[4]

[3] IATA Executive Summary Net Zero Roadmaps, 2023: https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/executive-summary---net-zero-roadmaps.pdf

[4]Gierens, K., Sausen, R., Bauder, U., Eckel, G. et al. (2024). "Influence of aviation fuel composition on the formation and lifetime of contrails – a literature review." Report prepared for Concawe Special Task Force on Aviation Fuels (FE/STF-28). Report number 1/24, https://www.concawe.eu/wp-content/uploads/Rpt_24-1-1-Copy-2.pdf.

These specific properties of SAF are of particular interest to the aviation industry as aircraft soot emissions contribute to non-CO_2 climate and air quality impacts, thus, measures to reduce them would have a positive impact on aviation environmental impact. Furthermore, contrail formation is induced primarily by PM emissions from aircraft engines. Reductions in PM emissions associated with SAF usage, as well as cleaner engines, can modify the ice crystal properties of contrails in a way that reduces their lifetime, radiative and climate impact (Märkl et al., 2024; Bier and Burkhardt, 2022; Teoh et al., 2022). Similarly, reductions in PM emissions during the landing and takeoff (LTO) phase can reduce the negative impact on LAQ in the vicinity of airports.

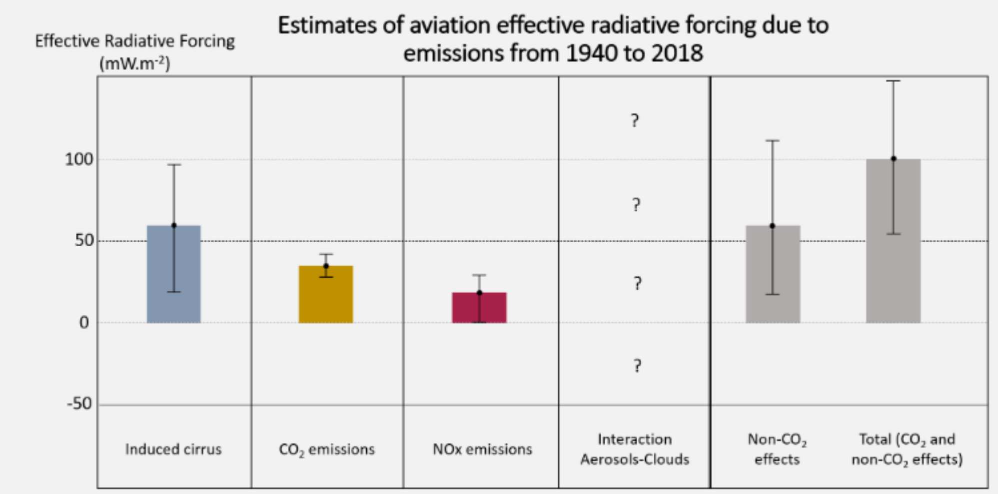
Given the limited SAF supply in the near future and its gradual introduction into the market, achieving and maximizing these environmental benefits requires strategic planning as well as overcoming existing barriers in aircraft compatibility, supply chain, and fuel infrastructure to facilitate the smart use of SAF. These benefits resulting from the reduction of aircraft particulate emissions can also be achieved through new engine technologies (i.e., lean burn combustors) or by modifying conventional jet fuel (CAF) properties.

This document provides a synthesis of the current scientific understanding of the physical processes and potential non-CO_2 climate benefits generated by using SAF (or fuels/engine technologies that reduce particle emissions). Some of the studies and processes are discussed in technical detail to provide interested readers with information to understand the complexities and uncertainties involved. Key points summarizing the main take-aways are provided at the end of each section. Finally, a high-level overview of some of the challenges and barriers associated with implementing strategies that would maximize the non-CO_2 co-benefits of SAF usage is presented at the end of the document.

2. The non-CO_2 climate impact of air transportation and the potential co-benefit of SAF usage

Non-CO_2 emissions (e.g., particulate matter, NOx, SOx, water vapor) have an indirect warming effect on the climate. The climate impacts of non-CO_2 emissions are short-lived in comparison to that of CO_2 which remains in the atmosphere for hundreds to thousands of years. Contrail cirrus constitutes the largest fraction of aviation's total non-CO_2 climate impacts (Lee et al., 2021). Even accounting for the large uncertainties, the contrail cirrus impact remains a large contributor to the warming effect of air transportation – likely at least equal to half of the CO_2 impact (Figure 2). Targeting contrails for mitigation can be a way to reduce aviation's climate impact in the near-term.

Figure 2: Effective radiative forcing from CO_2 and non-CO_2 climate forcers.



Estimates of the main contributions to effective radiative forcing, in mW.m^{-2}, from global aviation in 2018 resulting from emissions since 1940, according to Lee et al. (2021). From left to right, the terms are aviation-induced cirrus forcing in regions supersaturated with ice, carbon dioxide (CO_2) emissions, nitrogen oxides (NOx) emissions, and interactions between aviation-emitted particles (aerosols) and natural clouds. Current scientific knowledge does not allow an estimate of the latter term. The two grey bars on the right give the sum of the non-CO_2 forcing terms and the total forcing. The error bars indicate the 5-95% confidence interval.

Source: The Climaviation website (https://climaviation.fr/en).

The following section provides a bird's-eye view of contrails' impact on climate and how SAF can help to mitigate it. Different measurement campaigns are reviewed first to understand the correlation of fuel properties on aircraft particle emissions and contrail properties. Then the role of modeling in assessing the climate benefit through particle emissions reduction is highlighted.

2.1. Contrail-cirrus climate impact and the role of particulate emissions

Contrails impact the climate by interacting with both solar and terrestrial radiation which modify the energy balance of the Earth. The ice crystals that contrails are made of reflect some of the incoming shortwave radiation from the Sun (cooling cloud albedo effect) and absorb and reemit outgoing longwave radiation from the Earth (warming cloud greenhouse effect). The amount of radiation reflected or absorbed is dependent on the contrail's microphysical properties (i.e., mass, ice crystal number concentration, shape, and size) and its lifetime. A contrail's microphysical properties determine its optical depth or thickness, which is a measure of how much radiation is scattered or absorbed through the contrail. The net radiative forcing, or perturbation to the Earth's energy balance, of a single contrail is calculated as the difference of the net radiation flux (longwave plus shortwave) at the top of the atmosphere for a situation with and without the contrail. This difference depends both on contrail properties and on the ambient conditions, including surface albedo, presence of other clouds, sun angle, etc.

Depending on fuel properties and the engine type, aircraft emit different amounts and types of particulates which can affect the microphysical properties of a contrail. Most of today's aircraft emit significant amounts of soot particles, a type of nonvolatile particulate matter (nvPM), which are the result of the incomplete combustion of hydrocarbons. These solid particles, which are on the order of tens of nanometers (nm), allow water vapor to condense and freeze into the ice crystals that compose contrails. At a first order approximation, the higher the density or concentration of ice crystals, the larger the climate impact. This relationship is approximately linear in the so-called "soot-rich" regime where the emissions index of soot particles (EI_{soot}), or the number of emitted soot particles per kg of fuel, is above a certain threshold (EI_{soot} > ~1014-1015) as is the case with most of today's aircraft. Below this threshold, in the "soot-poor" regime, smaller ultrafine particles, or volatile particulate matter (vPM), emitted from the exhaust or entrained into the plume from the ambient air may contribute to the formation of ice crystals, thereby increasing the concentration and potentially the climate impact of the contrail. The theory behind this relationship between particulates emitted by an aircraft and ice crystal concentration is described in more detail in Appendix A.

Reducing the number of emitted particles from an aircraft's engine, using SAF or fuel with low or no aromatic content is expected to produce optically thinner contrails with lower ice crystal concentrations by reducing both the longwave and shortwave radiative impact. Additionally, the contrails' ice crystals are also expected to be larger as the available water vapor is deposited onto fewer ice crystals, which can subsequently shorten the lifespan of the contrail as the larger ice crystals will sediment out sooner (i.e., yield to the downward force of gravity). Due to these two effects, reduced optical depth and shorter lifespan, most SAF-induced contrails are expected to have a smaller net radiative impact than CAF-induced contrails which may reduce the climate impact of the former. While this relationship is robust in the soot-rich regime, there is still significant uncertainty regarding the role of vPM (e.g., sulfuric acid, lubrication oil, and organic compounds) in the soot-poor regime. Furthermore, the use of SAF results in an increase in the water vapor emissions index (EI_{H2O}) of approximately 10% which could add to contrail formation. While most studies indicate that this additional warming effect is negligible (Narcisco et al., 2021; Teoh et al., 2020), it remains an open question.

Ground and in-flight measurement campaigns have shown that using SAF can lead to a reduction in soot emissions and thereby reduce the initial number of ice crystals in the soot-rich regime. More data are needed to improve our scientific understanding of the impact that particle emissions from SAF have on ice nucleation processes, particularly the role of vPM in the low-soot regime. These data are also necessary for developing and validating the parameterizations used to represent contrail formation in numerical contrail and climate models which are used to evaluate the radiative and climate impact of contrail cirrus. A few global contrail modeling studies have shown that contrail cirrus radiative forcing (RF) decreases with reduced ice crystal particles associated with alternative fuels or cleaner engines, these studies do not currently account for the activation of vPM (Bier and Burkhardt, 2022; Teoh et al., 2022). More research is needed to better quantify this impact on the climate and constrain the uncertainties.

2.1.1 Impact of SAF on engine emissions

Numerous ground measurement studies in the past decade have provided strong evidence demonstrating the positive effects of lower aromatic and sulfur content in aviation fuel on reducing particulate emissions (Moore et al., 2015; Brem et al., 2015; Moore et al., 2017; Voigt et al., 2021; Märkl et al., 2024). One such study summarized ground tests from several measurement campaigns (APEX, AAFEX-I, AAFEX-II and ACCESS-I), analyzing the impact of fuel properties from 15 different aviation fuels combusted by CFM56-2-C1 engines on nvPM and vPM (Moore et al., 2015). The analyses indicate that the naphthalene (an aromatic compound) content of the fuel determines the magnitude of the nvPM emissions number and that reducing both fuel sulfur and naphthalene content to near zero levels would result in roughly a 10-fold decrease in the aerosol number emitted per kilogram of fuel burned. Another study reports similar findings from their ground tests with a significant increase in EI_{soot} (60%) when varying aromatic content from 17.8% up to 23.6% (Brem et al., 2017). Furthermore, they found increasing soot emissions with increasing naphthalene content (0.78% to 1.18%), while keeping the total aromatic content constant. Results from laboratory tests support the above field tests, indicating that naphthalene is the aromatic species in jet fuel that contributes the most to soot formation (Richter et al., 2020).

In-flight measurements have also been made to assess the impact of blended SAF fuel with low-aromatic and low-sulfur content on particulate emissions and show similar findings. One study found that using a synthesized paraffinic kerosene from hydrocarbon - hydroprocessed esters and fatty acids (HEFA-SPK) blend reduced the nvPM emissions from the CFM56-2-C1 engines by 50-70% (Moore et al., 2015). Similarly, another study reported a reduction of up to 50% in emissions associated with the use of SAF blends (Schripp et al., 2022). In addition, most of these studies confirm that nvPM emissions correlate well with fuel hydrogen content which increases with decreasing aromatic content.

2.1.2 Impact of SAF on contrail formation

While the above studies link reductions in fuel aromatic (i.e., naphthalene) and sulfur contents to reductions in particle emissions, the Emission and Climate Impact of Alternative Fuel (ECLIF) in-flight campaigns studied their impact on a contrail's microphysical properties. One of the objectives of the ECLIF campaigns was to investigate the effects of aromatics, namely naphthalene, content in SAF blends on soot emissions and ice particle formation in contrails. A series of flight campaigns conducted over several years provide strong experimental evidence that SAF can reduce both soot emissions and ice crystal numbers (Märkl et al., 2024).

The ECLIF1 and ECLIF2 campaigns which took place in 2015 and 2018, respectively, evaluated the impacts of four samples of 100% Jet A1 fuel types with samples of Jet A1 blended with Fischer-Tropsch (FT) based SAF (SSF1) and two varieties of HEFA-SPK based SAF, accounting for their differing fuel properties as indicated in Table 1.

Table 1: Fuel properties for the different fuels used during the ECLIF1 and ECLIF2/ND-MAX measurement campaigns.

Table 1 Properties of fuels burned during the ECLIF1 and ECLIF2/ND-MAX experiments.

ECLIF fuels	Ref1	Ref2	Ref3	Ref4	SSF1	SAF1	SAF2
Fuel composition	100% Jet A1	100% JetA-1	100% Jet A1	100% Jet A1	59% Ref1+ 41% FT-SPK	51% Ref3+ 49% HEFA-SPK	70% Ref4 +30% HEFA-SPK
Aromatics (vol%) (ASTM D6379) SASOL/ Petrolab	**18.8** (±2.5)	**17.2** (±2.5)	**18.6** (±2.5)	**16.5** (±2.5)	**11.4** (±2.5)	**8.5** (±1.5)	**9.5** (±1.5)
Naphthalenes (vol%) (ASTM D1840)	**1.51** (±0.07)	**1.83** (±0.08)	**1.17** (±0.06)	**0.13** (±0.02)	**0.82** (±0.05)	**0.61** (±0.04)	**0.045** (±0.01)
Hydrogen content (mass%) (NMR ASTM D7171)	**13.67** (±0.14)	**13.73** (±0.08)	**13.65** (±0.05)	**14.08** (±0.18)	**14.36** (±0.02)	**14.40** (±0.07)	**14.51** (±0.04)
H:C ratio (NMR ASTM D7171)	**1.89** (±0.02)	**1.90** (±0.01)	**1.88** (±0.01)	**1.95** (±0.02)	**2.00** (±0.01)	**2.00** (±0.01)	**2.02** (±0.01)
Specific Energy (MJ/kg) (ASTM D3338)	**42.80** (±0.02)	**43.20** (±0.02)	**43.14** (±0.01)	**43.34** (±0.01)	**43.50** (±0.02)	**43.63** (±0.01)	**43.63** (±0.01)
Sulfur Total (mass%) (ASTM D2622) SASOL/ Petrolab	**0.117** (±0.003)	**0.135** (±0.003)	**0.012** (±0.001)	**<0.001** (±0.001)	**0.057** (±0.002)	**0.007** (±0.001)	**<0.001** (±0.001)

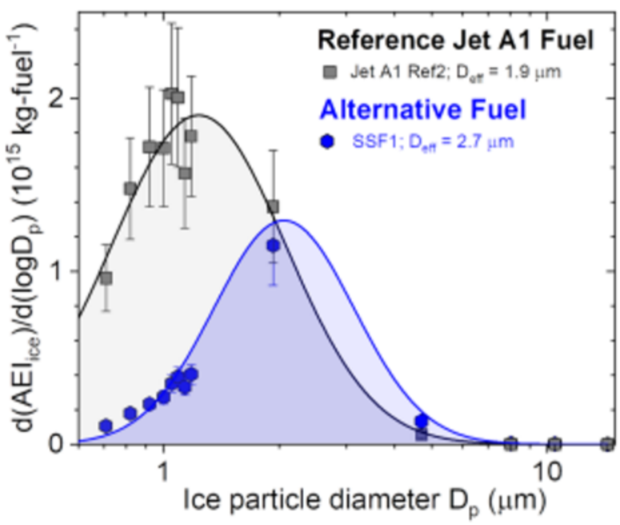
Fuel properties (± uncertainties according to certification standards) for fuels used for the contrail observations during ECLIF1 and ECLIF2/ND-MAX. Four reference fuels (Ref1 to Ref4), the semisynthetic jet fuel blend SSF1 and the sustainable aviation fuel blends SAF1 and SAF2 were probed in flight and/or in ground tests. Ref1 and Ref4 fuels were only included in the ground tests and were used for creating the alternative fuel blends. At similar atmospheric conditions, contrails were only observed on Ref2 fuel and on the alternative fuel blends SSF1, SAF1 and SAF2. Aromatics were determined by gas chromatography according to certification standard[56] ASTM D7566 by SASOL and Petrolab, the sulfur content was determined by SASOL for ECLIF1 and by Petrolab for ECLIF2/ND-MAX according to standard[57] ASTM D2622. Other components were measured by DLR, bi-cyclic naphthalenes according to certification standard method[58] ASTM D1840. The hydrogen content and the H:C ratio were measured using nuclear magnetic resonance relaxometry according to the standard[55] ASTM D7171 standard. Fuel properties were measured in the laboratory after the flight tests.

Source: Voigt et al. (2021)

Voigt et al. (2021) reported that significantly lower soot and apparent ice particle number emissions were associated with the SAF blends. Soot emissions indices for the HEFA-based SAF blends were 45–53% lower than the Ref2 Jet A1 fuel, consistent with previous studies (Moore et al., 2017). In addition, Voigt et al. (2021) also reported that the FT-based blend resulted in an EI_{soot} reduction of ~50%. The soot particle reductions associated with all SAF blends led to 45–74% lower ice crystal number concentrations compared to the Ref2 Jet A1 fuel. More specifically, they found that SAF2, which had the highest fuel hydrogen content and the lowest naphthalene content, was associated with the lowest soot and ice emissions. Their results indicate that bi-cyclic naphthalenes are more efficient soot precursors than mono-cyclic aromatic or aliphatic hydrocarbon structures.

Theoretical studies show that the larger ice crystals sediment and sublimate faster. As a result, contrails with fewer ice crystals have a shorter lifespan in the atmosphere, and thereby less of an integrated climate impact (Burkhardt et al., 2018). Measurements from the ECLIF2 campaign confirm that the reduced ice crystal number concentration associated with the Fischer-Tropsch fuel blend (SSF1) also resulted in increased contrail ice crystal diameter compared to the Jet A1 contrail (Figure 3).

Figure 3 : Apparent ice emission index distribution with respect to contrail particle size.



Source: Voigt et al. (2021).

While the ECLIF1 and ECLIF2 campaigns investigated the impact of SAF blends on soot emissions and ice crystal number concentrations, the ECLIF3 campaign tested the effects of burning 100% HEFA-SPK compared to 100% Jet A-1fuel in an Airbus 350 with Rolls-Royce Trent XWB-84 engines in 2021. The aircraft engines used were more modern and produced fewer soot particles than the engine type used in the previous ECLIF campaigns. Furthermore, the reference Jet A-1 fuel was relatively clean, having a lower aromatic content (~13%) than the global average (Table 2).

Table 2: HEFA-SPK and Jet A-1 fuel properties used in ECLIF3.

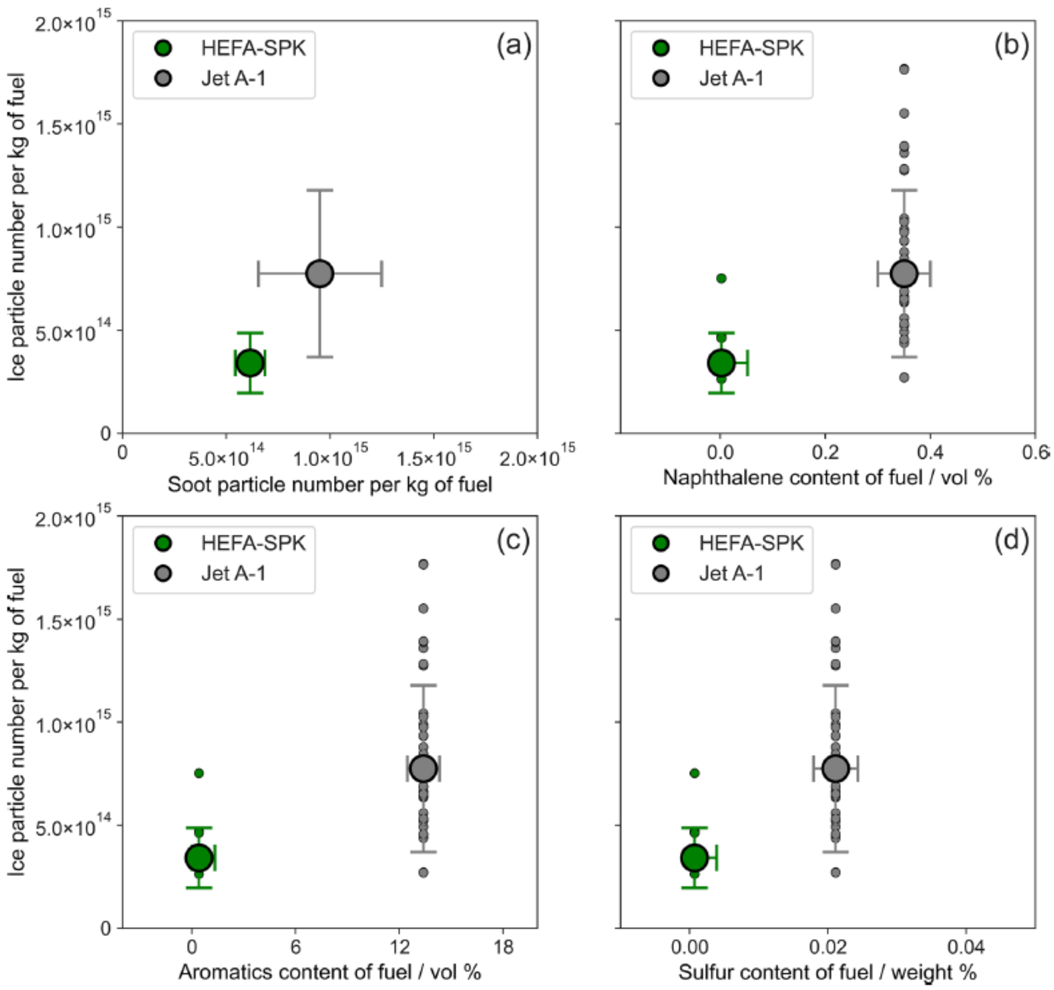
	Jet A-1	**HEFA-SPK**
Fuel Composition	100%	100%
Aromatics (vol %) (ASTM D6379)	13.4	0.41
Naphthalene (vol %) (ASTM D1840)	0.35	0.002
Hydrogen content (mass %) (ASTM D3701)	14.08	15.11
Carbon content (mass %)	85.90	84.89

H:C mole fraction ratio	1.95	2.12
EI_{CO2} (g kg-1)	3149	3111
Sulfur total (mass %) (ASTM D5453)	0.0211	0.0007

Source: Märkl et al. (2024).

A 35% reduction in emitted soot particles for 100% HEFA-SPK compared to relatively clean (low aromatic) Jet-A1 fuel and a 56% reduction in corresponding ice crystal numbers was measured during the ECLIF3 campaign as clearly depicted in Figure 4 (Märkl et al., 2024). Results suggest that the larger reduction in ice crystals could be due to the much lower sulfur content of the SAF compared to the Jet A-1 (-97%). The gaseous SO2 molecules emitted in the exhaust can condense into sulfates and coat the soot particles, making them more hygroscopic and likely to be activated as cloud condensation nuclei for the formation of ice crystals. Further analysis of the data indicates that the primary soot particle diameter controls the water activation rather than the effective sizes of soot aggregates as previously assumed (Yu et al., 2024). Since the primary soot particle diameter produced from engines burning SAF is smaller than that burning CAF, a higher level of supersaturation is needed for water activation to occur (Kärcher, 2018). This would increase the probability of smaller vPM becoming water activated and contributing to the total number of ice crystals (see Appendix A).

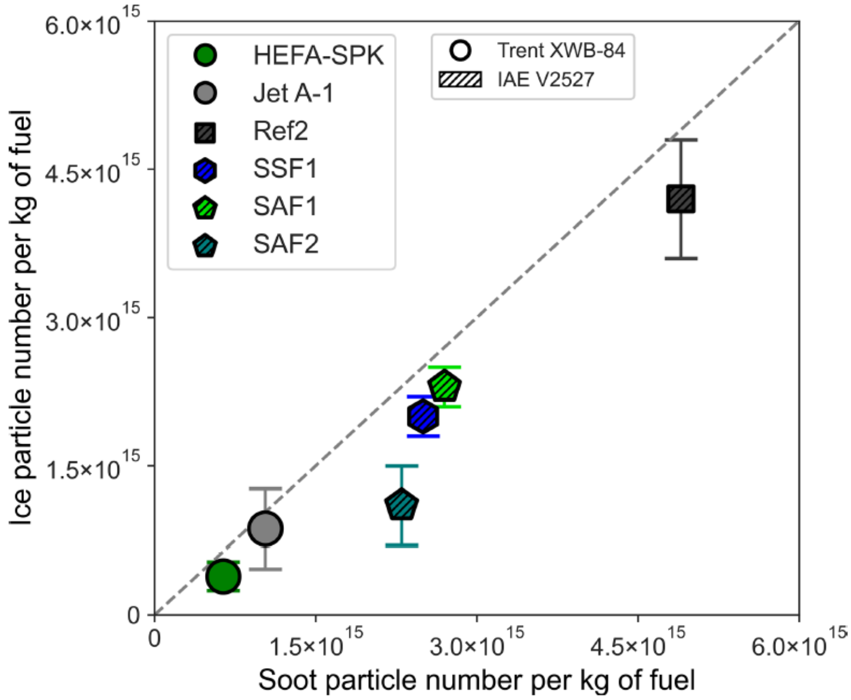
Figure 4 : The number of ice crystals per kg of fuel versus (a) nvPM emission indices and fuel properties (naphthalene, aromatic and sulfur content) measured during the ECLIF3 campaign.



Source: Märkl et al. (2024).

Comparisons were also made with the results from the previous ECLIF campaigns to qualitatively assess the impact of engine type and fuel parameters (Figure 5). Despite only using blended SAF, the contrails had a much greater reduction in both soot particle emissions and ice crystal numbers than the Ref2 contrail when compared to the reduction achieved in the ECLIF3 campaign, pointing to the role played by the engine, as older engines produce more soot. The ECLIF3 Jet-A1 fuel had a higher content of aromatics and sulfur than the SAF blends, but the contrail still had fewer ice crystals thanks to the newer RR engine which produces considerably fewer soot particles compared to the older generation IAE V2527 used in the previous campaigns. Results from the ECLIF campaigns indicate that higher hydrogen content fuels as well as cleaner engines with lower particle emissions can lead to reduced climate forcing from contrails, if soot particles remain in the soot-rich regime.

Figure 5: The number of ice crystals per kg of fuel versus nvPM emission indices measured during the ECLIF-1, -2, and -3 campaigns. See Table 1 for legend description.



Source: Märkl et al. (2024).

The microphysical properties of contrails (e.g., ice crystal size and density) significantly influence their radiative effects and persistence. As demonstrated by numerous measurement campaigns, these properties are largely determined by the amount and type of particulate matter that is emitted from an aircraft engine, which in turn depends indirectly on the type and composition of the fuel, and on the combustion process. Due to the reduction in emitted soot particles, the magnitude of the radiative and climate impact from SAF-induced contrail can potentially also be reduced.

The measurements described above are based on emissions in the soot-rich regime where vPM did not play a significant role in contrail formation. Recent measurement campaigns (i.e., VOLCAN, NASA's ecoDemonstrator) have focused on evaluating the impact of SAF combined with new engine technology (i.e., lean burn combustors) on particle emissions and contrail formation and microphysical properties. Although the results are not yet published, preliminary analyses presented at various conferences support theoretical model predictions of vPM becoming increasingly more significant as cloud condensation nuclei when EI_{soot} values fall below a certain threshold between ~10^{14} to 10^{15} (Kärcher, 2018; Yu et al., 2024). While these data provide critical input for developing physically based model parameterizations of the dependence of contrail ice crystal properties on both vPM and nvPM emissions in the soot-poor regime, more in-situ measurements are still needed.

Key points

- Naphthalene, an aromatic compound, has been shown to be a key precursor to soot emissions from jet engines.
- In-flight measurement campaigns have shown that aircraft engines burning SAF blends of up to 50% with low naphthalene and sulfur content can significantly reduce soot emissions and produce contrails with fewer, larger ice crystals compared to CAF.
- A limited number of in-flight measurements taken in the soot-poor regime (< ~10^{14} particles per kg fuel) confirm theoretical model predictions that emitted ultrafine volatile particulates (e.g., sulfuric acid, lubrication oil, and organic compounds) can serve as cloud condensation nuclei, resulting in an increase in contrail ice crystal number concentrations.

2.1.3 Assessing the contrail climate benefits of SAF

Evaluating the radiative and climate effect of SAF on contrails is complex and impossible to measure directly. Numerical contrail and climate models are required to estimate the impacts. These models range in complexity, offering trade-offs between computational demand and sophistication. Regardless of their complexity, all models that attempt to simulate highly complex, interdependent, and sometimes nonlinear processes on a wide range of spatiotemporal scales are associated with some uncertainty. These uncertainties are due either to a lack of scientific understanding of certain processes (i.e., the role of vPM in ice crystal formation) or to simplifications in how processes are numerically represented in models.

Despite their limitations, numerical models are our only tools for assessing climate impacts and achieving a better understanding of the interdependency and nonlinearity of relevant processes associated with various climate forcers. Numerous studies employ such models to investigate the impact that reductions in soot emissions obtained from using SAF or CAF with lower aromatic contents might have on contrail radiative forcing and climate impact. It should be noted that the models used in the studies presented here did not account for potential vPM water activation in the formation of contrail ice crystals and, in cases where EI_{soot} is in the poor-soot regime (see Appendix A), may overestimate the potential contrail climate benefits from SAF and cleaner burning engines. While model parameterizations are currently being developed to represent these processes, more scientific understanding based on in-situ measurements is needed so that they can be accurately represented.

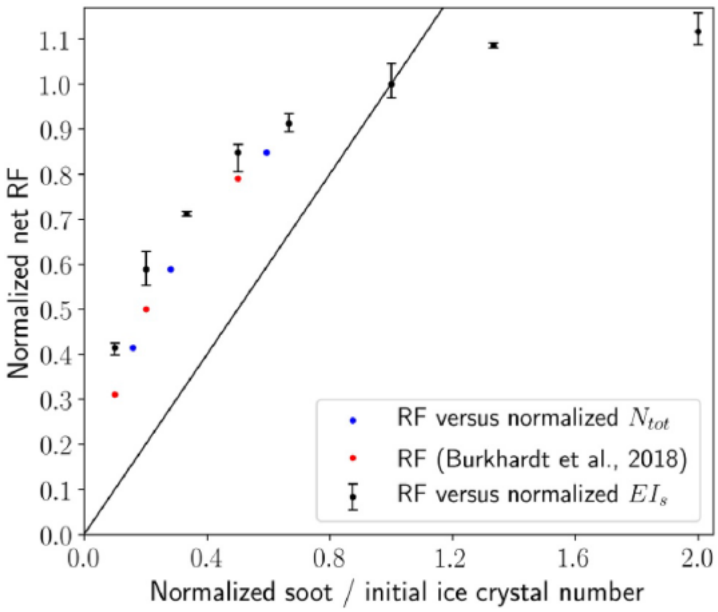
Contrail formation, evolution, and persistence

The global climate model (GCM) ECHAM-CCmod has been used extensively to study the radiative and climate impact of contrail cirrus. Results from a study investigating the climate impact of reductions in soot emissions and, hence, initially formed ice crystal numbers, indicate a nonlinear impact on radiative forcing due to the nonlinear nature of associated processes (Burkhardt et al., 2018). Using an updated version of the model which includes a parameterization for ice crystal losses during the vortex phase and the dependency of ice nucleation on the difference between the ambient temperature and contrail formation threshold, Bier and Burkhardt (2022) estimate a nonlinear dependency of global RF on soot emissions reductions (Figure 6).

Reducing present-day soot emission (1015 particles per kg of fuel) by 50%, 80%, and 90% leads to corresponding reductions in ice crystal numbers (after the vortex phase, see Box 1) of approximately 41%, 72%, and 84% and cause the global RF to decrease by approximately 15%, 41%, and 59%, respectively. The estimated impact of reduced soot emissions on RF is slightly less than previously reported in Burkhardt et al.

(2018) with an earlier version of the model due to the improved representation of the two processes mentioned above. Namely, reduced ice crystal loss within the vortex phase partially counteracts the decrease in the nucleated ice crystal number because fewer larger ice crystals sublimate.

Figure 6: Relationship between normalized soot number emission indices and the global mean normalized net radiative forcing by contrail cirrus (black circles). Bars indicate the full range of single year mean radiative forcings, and on the normalized globally summed total ice crystal number after the vortex phase (blue circles). Mean net radiative forcing depending on the normalized initial contrail ice crystal number as calculated by Burkhardt et al. (2018) (red circles) with previous version of model.



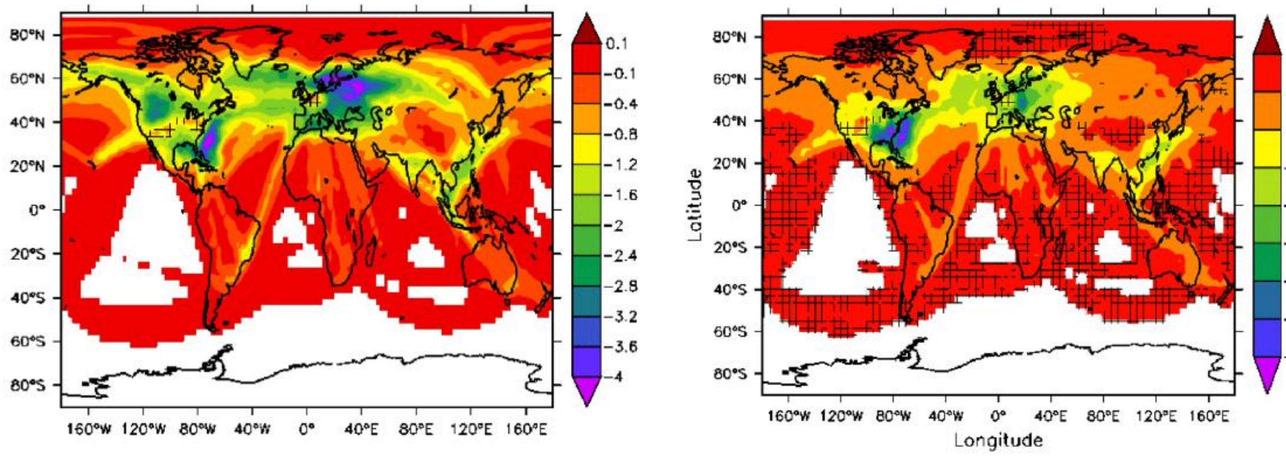
Source: Bier and Burkhardt (2022).

Box 1: Vortex phase

Within a few seconds after ice crystals are formed, the aircraft exhaust plume mixes with the wake vortices (circulatory airflow patterns) formed behind the aircraft during the so-called contrail "vortex phase". During this phase, many ice crystals can sublimate due to adiabatic heating as the contrail is forced downward in the wake. This partial loss of ice crystals due to sublimation can be significant (>80%) and is dependent on ambient temperature, relative humidity over ice, the number of nucleated ice crystals, Brunt-Vaisala frequency (a measure of atmospheric stability), the weight and wingspan of the aircraft, and the water vapor emission (Unterstrasser, 2016). Ice crystal loss during the vortex phase is expected to be reduced SAF-induced contrails due to the larger ice crystal sizes. Therefore, the climate benefit of alternative fuels cannot be inferred solely from the reduction of the EIsoot or the initial crystal concentration, and ice sublimation during the vortex phase must also be considered.

Significant regional differences in the impact of soot emissions reductions on the RF are highlighted in Bier and Burkhardt (2022). Regions exhibiting the highest impact potential such as the eastern US, North Atlantic, and eastern Europe could be targeted for increased SAF use while supplies are limited (Figure 7).

Figure 7: Global distribution of absolute differences (80% reduced soot minus present-day soot) in contrail cirrus coverage with optical thickness of at least 0.05 in % (left) and net radiative forcing by contrail cirrus in mWm−2. Hatched patterns are not statistically significant at the 99% level.



Source: Taken from Bier and Burkhardt (2022).

For example, colder regions at higher latitudes will have greater potential for reductions in ice nucleation since the ambient temperatures are generally well below the contrail formation threshold and ice crystal numbers are close to the number of emitted soot particles. Furthermore, the lifetime of a contrail is largely determined by the prevailing synoptic conditions, and under certain conditions, the larger ice crystals produced in a SAF-contrail become more significant in reducing the lifetime of the contrail than other conditions in which ice crystals are subject to adiabatic heating and sublimation (Bier et al., 2017)).

The climate benefit of a SAF-contrail will be maximized if the synoptic situation allows the ice crystals to grow large enough to reach their terminal velocity and sediment into subsaturated layers. However, if the synoptic situation forces the airmass downward into subsaturated layers, the ice crystals will sublimate irrespective of their size and the climate benefit of a SAF-contrail will be reduced. The use of meteorological information can therefore help determine how to best optimize SAF usage on selected flights to maximize non-CO_2 benefits (Gierens et al., 2016; Bier and Burkhardt, 2022; Teoh et al., 2022).

While the impact of reduced soot particles and initial ice crystal numbers on contrail cirrus RF is relatively straightforward in the present-day soot-rich regime, the corresponding changes on the climate impact measured in terms of surface temperatures are more difficult to assess since contrail cirrus lifetimes and the impact of RF on surface temperatures also need to be considered (Bier and Burkhardt, 2022). Moreover, the climate efficacy of contrail cirrus, which quantifies the change in global surface temperature response per unit of contrail RF, is not well constrained or quantified. Therefore, the actual climate benefit resulting from SAF usage is difficult to quantify precisely. In addition, while reduced soot emissions can shorten the lifespan and reduce the total radiative effect of persistent contrails, the ambient meteorological conditions, which are highly variable, could have even more of an impact on both factors. To put this into perspective, a SAF-contrail and a kerosene-contrail in the same ambient conditions may differ less than two contrails from the single fuel type under different meteorological regimes (Gierens et al., 2016).

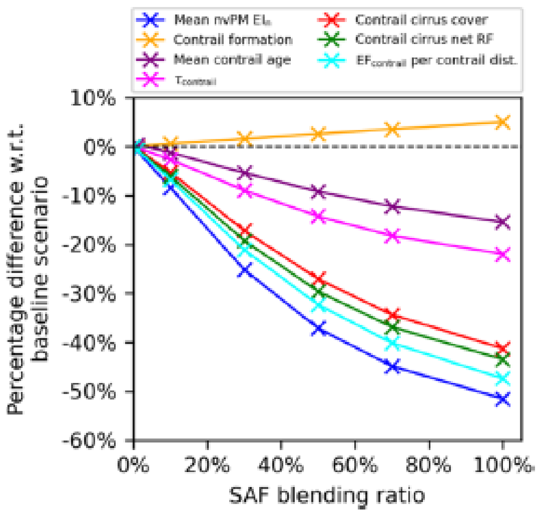
Large-scale climate impact assessment

The trajectory-based plume model, Contrail Cirrus Prediction Tool “CoCiP” (Schumann et al., 2012), has also been used extensively to study the radiative impact of contrail cirrus and potential co-benefits of SAF (Bier et al., 2017; Narcisco et al., 2021; Teoh et al., 2022). CoCiP is a Lagrangian (particle following) model that simulates the life cycle of contrail cirrus from single flights or a fleet of aircraft. Like GCMs, simple bulk parameterizations are used to simulate contrail ice properties which are initially dependent on parameters such as aircraft type and fuel properties. A radiative transfer scheme is used to estimate the energy forcing of the contrail. A limitation of plume models such as CoCiP is the lack of feedback with meteorology and clouds for which a GCM is necessary to simulate.

The benefit of using a more simplified model such as CoCiP is its greater computational efficiency and that it can simulate contrail cirrus on a flight-by-flight basis which is useful when comparing the impact of different aircraft/engine types and fuel properties on the contrail cirrus radiative forcing of individual flights. Nevertheless, it should be noted that the uncertainty associated with RF estimates for individual flights is considerably higher than when averaged temporally (e.g., annually) and/or spatially (e.g., regionally or globally). This is due to the large variability in the radiative flux of individual contrails (+/- 100 W m2) due to the meteorological conditions which strongly impact a contrail's lifetime and microphysical properties (Gierens et al., 2016; Wilhelm et al., 2021). Over several years, the meteorological influences average out, so the radiative and climate effects of contrails are best determined over longer time periods.

Teoh et al. (2022) utilized the CoCiP model to quantify the change in contrail properties and climate forcing in the contrail-prone North Atlantic region using different blending ratios of SAF based on a fuel hydrogen content-based soot emission relationship (Teoh et al., 2022). In an idealized scenario where all aircraft use 100% SAF, they estimated a 51% and 55% reduction in EI_{soot} and ice crystals concentration, respectively, but an increase in the formation of persistent contrails of about 1% due to the higher EI_{H2O} (Figure 8). As mentioned previously, the potential climate benefits reported in this study may be an upper bound estimate because the activation of vPM is not considered.

Figure 8: Relative difference in the fleet-aggregated EI_{soot}, contrail properties, and climate forcing in the North Atlantic for different SAF blending ratios relative to the baseline scenario where conventional fuels are used.

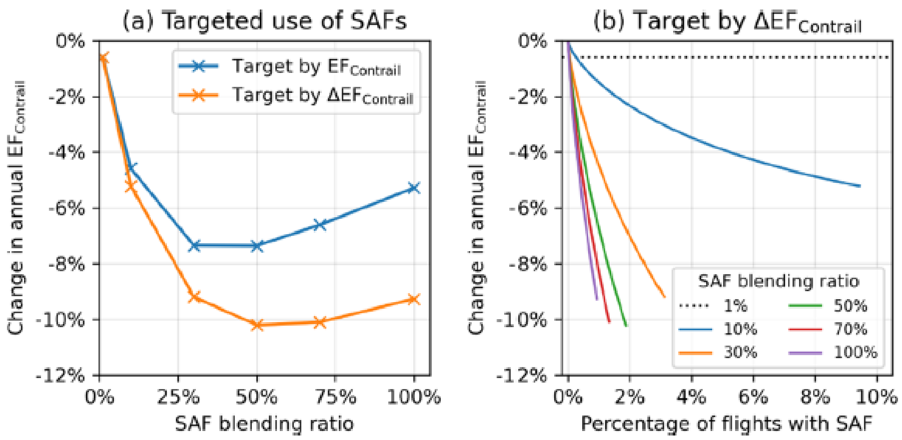


Source: Teoh et al. (2022a).

The researchers found that the increase in persistent contrails is offset by the decrease in mean contrail lifetime (~15%) due to the larger ice crystals resulting from the higher EI_{H2O} and lower nvPM EIn. In terms of radiative impacts, significant reductions in the annual mean contrail cirrus net RF (−44%) and EFcontrail per contrail distance (−47%) are estimated, though these are slightly below the estimate of Bier and Burkhardt (2022).

While SAF supply volumes remain low, Teoh et al. (2022) propose that blending at higher ratios and targeting usage to a fraction of flights responsible for the most strongly warming contrails could optimize the non-CO_2 co-benefits from SAF usage by a factor of 9-15. Previous studies have also estimated that only a small fraction of flights are responsible for most of the contrail cirrus RF (Teoh et al., 2020; Teoh et al., 2022). Their results indicate that there is a larger reduction potential in contrail cirrus RF for lower SAF blending ratios compared to the relative effect of higher blending ratios in the North Atlantic region because after a certain point, concentrating the limited SAF supply to only a few flights becomes less efficient (Figure 9). In other words, not as much climate benefit is gained when using 100% SAF versus a 50% blend compared to a 10% blend, therefore blending ratios of 30% - 50% may be optimal. On the other hand, a lower SAF blend ratio (i.e., 5% - 20%) would allow the spread of the limited supply of SAF across a higher number of flights, thereby reducing the risk of forecast errors in identifying the flights with the most strongly warming contrails. Furthermore, a larger reduction in RF is achieved when allocating SAF to flights based on their energy-forcing reduction potential (ΔEFcontrail) rather than the absolute value of a flight's EFcontrail (older aircraft with engines that produce more soot would have a larger ΔEFcontrail). The authors also suggest that targeting the flights that form these contrails, mainly at night and during the winter, would also contribute towards minimizing contrail climate impacts from aviation. Although not analyzed in this study, a more feasible strategy to implement may be to target specific flight routes that have the highest contrail climate warming, rather than specific flights that would require a level of skill and confidence in upper atmosphere weather forecasts that does not exist today.

Figure 9: Change in the annual contrail energy forcing in the North Atlantic as a function of (a) SAF blending ratio that is provided to flights with the largest energy forcing (blue line) and change in energy forcing (i.e., reduction potential) (orange line) and (b) the percentage of flights that is targeted with SAF from the different blending ratios.

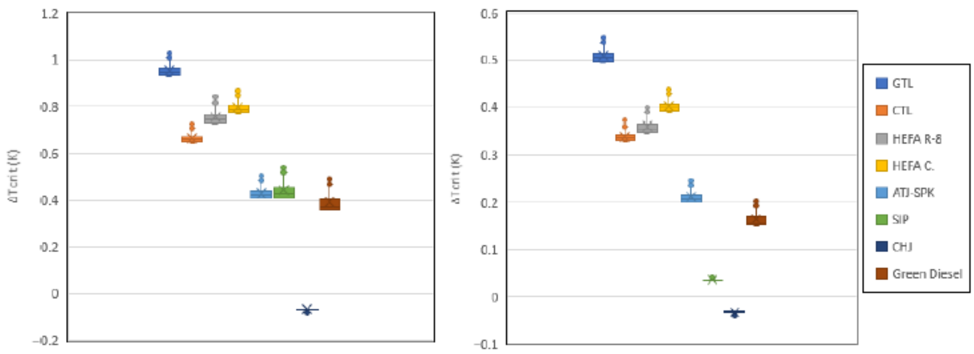


Source: Teoh et al. (2022a).

While Teoh et al. (2022) found that the impact of increased contrail formation associated with SAF's higher EI_{H2O} was minor, an earlier study performed by MIT in 2017 suggested that the impact was more significant and could increase the contrail cirrus RF compared to conventional fuel by up to 18% depending on the assumed ice crystal shape which can have a large impact on the amount of reflected short-wave radiation (Caiazzo et al., 2017). Based on these results, the authors of the MIT study suggested that by targeting SAF usage exclusively on nighttime flights, a reduction in contrail cirrus RF could be achieved. However, the logistical feasibility of implementing such a strategy was not addressed in their study and would need to be considered.

In contrast to the results of Teoh et al. (2020), other studies have found that the increase in EI_{H2O} associated with SAF does not have a significant impact on the reduction achieved in contrail cirrus RF due to reduced EI_{soot}. Utilizing the CoCiP model, Narcisco et al. (2021) found that various types of SAF had less than a 1% variation in contrail formation frequency due to higher EI_{H2O}. In fact, this resulted in slightly longer contrails, but not in new separate contrails (Figure 10).

Figure 10: Absolute differences in contrail formation threshold temperature between pure SAF and blends to conventional fuel.



(a) Pure SAF. (b) SAF blends.

Source: Narciso et al. (2021).

Except for Caiazzo et al. (2017), these studies support the conclusion that was put forth by Gierens et al. (2016) which suggested that a ~10% increase in EI_{H2O} in alternative fuels would lead to an increase in contrail threshold temperature of less than 1 K, which in turn corresponds to a lower minimum altitude for contrail formation of 100 to 150 m. They also noted that the effect of a higher EI_{H2O} is offset by a decrease in fuel heating value.

The inconsistency between the MIT results and other studies regarding increased EI_{H2O} not only highlights the need for more research and analysis, particularly regarding the impact of ice crystal shape on contrail shortwave forcing, but also illustrates the importance of comparing different modeling approaches and constraining uncertainties through sensitivity analyses. To this end, a study estimated the sensitivity of the radiative-only properties of contrails with respect to differences in ice crystal number concentrations to isolate their dependence on SAF usage (De León et al., 2023). Using a simplified radiative transfer model with prescribed ice crystal numbers (Nice) and ice water content (IWC), they found that the RF varied by a factor of 3 and 5 when assuming a ±30% and ±60% IWC range, respectively, suggesting that the differences in the prescribed IWC and Nice values in different models may explain the large discrepancies among RF estimates. Despite the potentially large variation, the authors report that their estimate, considering only radiative effects, of an 85% reduction in Nice results in a 35% reduction in RF, which they conclude is similar to the reductions estimated by Burkhardt et al. (2018) using a GCM and also accounted for changes in contrail cirrus optical depth and coverage (De León et al., 2023). Nevertheless, they emphasize that the accuracy and representation of Nice and IWC combined needs to be improved, namely through measurements, to better estimate contrail RF in models and to better understand its dependence on the use of SAF.

Other uncertainties also exist when assessing the climate benefit of alternative fuels on contrails, such as in the estimation of engine soot formation (Narcisco et al., 2021). Certain assumptions are made, which may not be valid such as soot particle size and engine power, as well as potential differences in these parameters depending on the type of fuel. For example, SAF blends with lower aromatics than typical Jet A-1 fuel have been shown to produce soot particles with a smaller mean radius (Kumal et al., 2020; Jasiński et al., 2024). These effects are not currently accounted for in most contrail modeling studies, although they may not be significant at temperatures below the contrail formation threshold. As discussed in Section 2.1.2, results from the ECLIF campaigns have led to some valuable insights, however, more data are needed to establish a correlation between a fuel's composition, engine power, and the aggregate and primary particle sizes ensuing from the combustion.

While it is difficult to compare results from the modeling studies presented here since they use different input data, different years, and cover various regions, etc., overall, these studies indicate a positive climate co-benefit of SAF. The tendency for large reductions in soot particle emissions, and hence ice crystal formation, likely leads to a reduction in the radiative impact of a contrail, although there remain uncertainties in precisely quantifying the value. It is also worth emphasizing that none of these models consider the role of vPM (see Appendix A). For certain cases, the assumption of a soot-rich regime may not be valid (i.e., cleaner engines with high SAF blends). Moreover, a reduction in soot particles and radiative impact does not necessarily mean that the climate impact is reduced which, in turn, depends on several additional parameters (surface albedo, met conditions, etc.).

Key points

- Global modeling studies show that reductions in soot emissions associated with SAF usage can lead to significant decreases in the net contrail-cirrus RF (~44% to 59%).
- Small increases in water vapor emissions (EI_{H2O}) associated with SAF usage may lead to a slight increase in persistent contrails or their path length. Most modeling studies suggest that this has a negligible effect on the contrail climate impact, though it remains an open question.
- Modeling studies suggest that targeting a few, limited flights that have the highest contrail warming potential based on geographic region (e.g., Europe, US and the North Atlantic region), time of year (i.e., winter), and time of day (e.g., late afternoon) for higher SAF blend usage could be an effective way to optimize the climate co-benefits of SAF. These studies do not account for the logistical issues and challenges associated with such strategies.

3. Challenges and Barriers

There is a significant amount of research supporting the climate and air quality co-benefits from the use of SAF or CAF with lower aromatic and sulfur contents, as presented in the previous sections. Aside from the uncertainties discussed, there are also challenges that exist in either the deployment and usage of SAF at higher blends or in producing cleaner CAF which would maximize the non-CO_2 co-benefits. In addition, while blended and certified SAF is a drop-in solution, using it neat, or unblended (100%) requires further work to make it fully compatible with existing distribution systems, storage infrastructure and aircraft. An overview of the logistical, technical, infrastructural, and economic challenges is presented in this section.

3.1. Using neat SAF or higher blends

Because neat SAF does not contain any aromatics, it is not compatible with all aircraft nor with the current aviation fuel infrastructure. To make SAF compatible and usable as a drop-in fuel, it must be blended (up to 50% as per current regulation) with CAF to a level that meets international standards regarding composition and performance. The ASTM international and others (e.g., UK Defence) set the technical aviation fuels standards. Any SAF blend must comply with the ASTM D7566 standard which specifies, among other criteria, that the aromatic content must be within the range of 8% - 25%. In this section, a high-level overview of the challenges associated with using SAF at higher blends is presented.

3.1.1 Aircraft compatibility

Aromatics in jet fuel ensure its safety and compatibility with all aircraft engines. SAF with low/no aromatic content is not compatible with most aircraft today. One of the main issues concerns the ability of the fuel to swell seals in the system. Aircraft fuel systems contain O-ring (elastomer) seals, and the high aromatic content of CAF encourages these seals to swell, providing more protection from leakage. In the case of fuel without aromatics, the seals tend to extract and shrink. Newer aircraft use seals that are compatible with 100%

paraffinic fuel (fuels with near zero sulfur and aromatics). However, there are still issues with older aircraft that use nitrile seals.

Another issue is related to the lower lubricity associated with low/no aromatic content of the fuel which can deteriorate the fuel pump more quickly over time. While the lubricity of the fuel can be improved with additives, this could lead to other problems that are not yet known or fully understood and require more experimental research. The lower density of SAF also affects fuel gauging, but this is not a major issue since adjustments to the gauging system can be made relatively easily. Finally, there are concerns regarding the poor electrical conductivity of the fuel which may lead to static charge build-up.

The problems associated with neat SAF usage can be overcome by adding aromatics to the fuel. In this case, however, the non-CO_2 co-benefits are lost, unless effort is made to keep the content near the minimum standard (i.e., 8%). There is ongoing work in the fuels community to investigate how and what aromatic species could be added back (i.e., excluding naphthalenes) into SAF while keeping particle emissions to a minimum to conserve the non-CO_2 benefits[5]. In the meantime, newer aircraft are being made compatible with neat SAF through different materials for the seals or calibrated gauging. However, fleet turnover is long with an average aircraft lifespan of 25-30 years, and older aircraft which are not certified for 100% SAF would need to be retrofitted and made SAF-compatible. Alternatively, airports would need to ensure the availability of both SAF and CAF. This would require separate storage and handling of both fuel types and careful management of aircraft refueling to prevent uploading the wrong fuel. Due to the high costs, and the complex logistical challenges, it remains more practical for airports to only stock blended fuel compatible with all aircraft.

3.1.2 Supply chain and airport infrastructure

Jet fuels are transported in bulk quantities to airports. Systems are often shared between fuel suppliers and other fuel products. Although there are requirements to separate jet fuel from other fuels, the same storage sites (different tanks) can be used, and vessels and pipelines can transport multiple kinds of fuels, with appropriate quality control measures. If a SAF blend is compliant with ASTM D1655, which defines the certification standards for CAF to ensure safety and consistency, it can be treated in the same way as conventional kerosene. However, the scaling up of SAF and strategies designed to maximize the non-CO_2 co-benefits (e.g., to designated flights or airports), would require separate storage and fuel supply infrastructure. This would also have implications for the book and claim system because SAF would need to be physically transported to specific airports and flights.

In the current airport design system, the shared use of tanks and supply lines prevents a segregated supply of particular fuel batches from being uplifted to individual aircraft.[6] From the airport storage tanks (i.e., fuel farm), aircraft are supplied either via underground hydrant systems or fuel trucks. Strategies aimed at maximizing the non-CO_2 co-benefits of SAF usage, such as targeting specific flights or airports, might require some restructuring of existing infrastructure. For example, an existing storage tank could be used for only SAF blends to avoid dilution with CAF and to ensure that the highest blended SAF possible are uplifted to aircraft serving the routes with the largest climate impact. Alternatively, blended SAF could be prioritized to selected airports qualified to optimize non-CO_2 co-benefits. For a supply of non-drop-in 100% SAF, a fully segregated system along the supply chain and at the airport would be needed. These different scenarios are being explored in different forums, such as within the EU 2020 horizon aLIGHT project where IATA is involved.[7]

As air transportation traffic is predicted to grow in the coming years, additional fuel production capability and infrastructure will be required to increase the capacity of pipelines, tank storage, and airport distribution

[5] **Anuar, A., Undavalli, V.K., Khandelwal, B. and Blakey, S. (2021). "Effect of fuels, aromatics and preparation methods on seal swell." *The Aeronautical Journal*, [online] 125(1291), pp.1542–1565, https://doi.org/10.1017/aer.2021.25.**

[6] **https://www.ati.org.uk/wp-content/uploads/2022/06/saf-integration.pdf**
[7] **https://alight-aviation.eu**

systems regardless of the fuel used. In these early planning and design stages, it may be wise to consider non-CO_2 co-benefit factors as well as the associated costs.

3.2. Altering fuel composition – feasibility, policy, and incentives.

Altering the fuel composition of CAF by reducing or removing the aromatic and/or sulfur content can also be an effective measure to help mitigate non-CO_2 impacts. The exact composition of crude oil, which varies largely depending on geographic origin, influences the fuel properties of the derived products such as jet fuel. Crude oil is comprised of thousands of different hydrocarbon compounds, as well as small amounts of impurities (i.e., sulfur, nitrogen, oxygen and certain metals). The ASTM and other standards define acceptable ranges for aromatic and sulfur content in conventional fuel. Refining processes exist for reducing the aromatics content of other fuel products (i.e., gasoline and diesel fuel) mainly to comply with regulations controlling emissions of criteria pollutants. These refining processes can be adapted to control the aromatics and naphthalenes content of CAF.

3.2.1 Aromatics

There are four main classes of hydrocarbons contained in jet fuel: normal paraffins, iso-paraffins, naphthenes, and aromatics. The aromatics compounds are beneficial because they enhance lubricity, lower the freezing point, and interact with polymer seals in the engines and fuelling systems to help prevent fuel leakage. Within the aromatics, there are different types of species, including naphthalenes, which are natural constituents of crude oil. Research has indicated that it is primarily naphthalenes that produce the soot particles, and, therefore, could be targeted for removal (e.g., Ritcher et al., 2020).

The two main refining technologies currently available for controlling the naphthalenes content of jet fuel are hydrotreating and extractive distillation. Hydrotreating is widely used in refineries for numerous applications and can be used to convert naphthalenes to aromatics or other hydrocarbons so there is little or no loss in the finished jet fuel volume. Extractive distillation, on the other hand, uses a solvent to completely remove the naphthalenes content from the jet fuel and results in a loss in volume.

The additional refinery processing for reducing or removing naphthalenes requires process fuel, steam, electricity, and, in the case of hydrotreating, hydrogen production via the steam methane reforming process, which has a relatively higher carbon intensity than some other processes (i.e., green hydrogen production via renewable energies). In addition to the increase in operating costs, the greenhouse gas emissions associated with each of these processes increase life-cycle jet fuel GHG emissions. A few studies have investigated the feasibility and costs of implementing naphthalenes removal at refineries (Barrett et al., 2021; MathPro Inc., 2023).

The FAA ASCENT project 039 study assessed the societal costs and benefits of removing naphthalenes from jet fuel produced in the United States (Barrett et al., 2021). They considered a hypothetical adoption of a policy whereby jet fuel naphthalene content in the US was reduced by 95% via either hydrotreatment or extractive distillation at 116 refineries with capacities in excess of 1,000 barrels per day. For hydrotreatment, the climate impacts of the refinery CO_2 emissions were found to exceed the expected air quality and climate benefits associated with the reduction in soot emissions. Furthermore, the net present value (NPV) of the climate warming associated with sulfur removal was greater than the NPV of the reduced air-quality-related damages. For extractive distillation, the median air quality and climate benefits were approximately equal to the societal cost of the refinery CO_2 emissions. In addition to these environmental costs, the costs associated with processing jet fuel in the refinery must also be considered. These results suggest that, in the absence of a strong contrail effect, naphthalene removal on a nationwide basis is unlikely to be cost-beneficial using either extractive distillation or hydrotreatment. However, the study suggested that naphthalene removal could be beneficial under certain circumstances, for example, if applied to fuels used at individual airports with particular air quality concerns, or if used at times and locations where the formation of warming contrails is most likely (Barrett et al., 2021).

The International Council on Clean Transportation (ICCT) also commissioned a study to assess the technological and economic feasibility of naphthalenes control in petroleum jet fuel (MathPro Inc., 2023). The study found that naphthalenes control in refineries through extractive distillation was considerably more costly than hydrotreating, mainly due to the significant loss in product volume. In addition, their analysis suggests that the average costs of naphthalenes control would be much higher in hydro-skimming refineries than in conversion refineries, mainly due to the large disparity in the average sizes of the two types of refineries and the consequent increase in unit capital costs.

Based on a preliminary cost analysis, the ICCT report indicated that the likely average refining cost of naphthalenes control in CAF would be in the range of about 7–37¢/gal, with US conversion refineries on the low end and US hydro-skimming refineries on the high end (MathPro Inc., 2023). The refinery cost of naphthalenes removal would vary considerably depending on factors such as the size and volume of jet fuel produced at the refinery as well as their existing infrastructure (e.g., presence of hydrocracker and potential for expanding or retrofitting jet fuel hydrotreating units already in place). Another consideration of implementing large-scale naphthalenes removal would be the follow-on effects that a cost increase might have on national and global patterns of jet fuel production and distribution. Strategies should be based on a holistic approach and take into account projected supply and demand of other transportation sectors (e.g., shipping and heavy-duty vehicles).

3.2.2 Sulfur

Sulfur is also naturally present in crude oil in varying quantities. At higher levels, sulfur can lead to undesirable effects such as hindering certain chemical reactions in the refinery process or corroding equipment. In jet fuel, sulfur can lead to emissions of sulfur dioxides (SO_x) which oxidize into sulfates in the engine exhaust. Sulfates can contribute to climate warming through their potential role as cloud condensation nuclei in contrail formation (see Appendix A). Sulfates can also be harmful to human health when emitted near the Earth's surface in populated areas.

The maximum limit for sulfur in jet fuel is 3,000 ppm, although the average concentration is thought to be around 600 ppm (Faber et al., 2022). Refineries must have the capability to remove sulfur from crude oil and refinery streams to the extent needed to mitigate the undesirable effects. The higher the sulfur content of the crude, the greater the required degree of sulfur control and the higher the associated cost. Although sulfur does not provide any benefits in fuel, refineries may just remove enough to meet the standard maximum to avoid additional costs.

Key points

- Global modeling studies show that reductions in soot emissions associated with SAF usage can lead to significant decreases in the net contrail-cirrus RF (~44% to 59%).
- Despite the climate and air quality benefits, fuel suppliers do not have any incentives to minimize the aromatic content of SAF blends, and often use CAF with high amounts to ensure that the blended product meets international standards.
- Strategies targeting SAF usage on selected flight routes with the highest contrail warming potential would require separate fuel storage and handling at airports. The associated restructuring of existing infrastructure can be cost-prohibitive.
- Removing the naphthalenes and sulfur from CAF can be an effective strategy in reducing the non-CO_2 impacts of air transportation. The two main refining technologies currently available to remove or reduce naphthalenes from CAF are hydrotreating and extractive distillation. From an economic perspective, hydrotreating may be more feasible at refineries with existing infrastructure because of the significant loss in volume associated with extractive distillation.
- Refineries have the capability to remove sulfur from crude oil and keep the maximum level below the 3000 ppm standard for CAF, but have no incentive to completely remove it due to the associated added costs.

4. Conclusions

Air transportation's non-CO_2 emissions have a significant warming impact on the climate. According to recent assessments, the impact is estimated between one-half to three times as much as the impact of aviation CO_2 emissions. Contrail-cirrus comprise a large fraction of aviation's total non-CO_2 effects. Despite the significant advances in the scientific understanding of the processes that govern contrail formation and evolution, there remain uncertainties that must be accounted for when developing mitigation strategies to ensure that a positive net climate benefit is achieved.

Numerous measurement campaigns have demonstrated that the naphthalenes content in jet fuel determines the majority of nvPM (soot) emissions, and that SAF (or other types of cleaner fuel) form contrails with fewer, larger ice crystals which may reduce the climate impact, but this assumption is only valid in a high-soot regime (~ > 1014 to 1015 particles per kg fuel). Below a certain threshold, and in certain ambient conditions, vPM emitted from the engine exhaust (e.g., sulfuric acid, lubrication oil, and organic compounds) may also start to contribute to the formation of ice crystals, potentially enhancing the climate impact of the contrail. More measurement campaigns of EI_{soot} in the soot-poor regime are needed to better understand the relationship between aircraft vPM emissions and the formation of ice crystals. Current scientific understanding indicates that mitigation efforts based on fuel composition should aim to reduce emissions of both nvPM and vPM simultaneously.

Optimizing fuel composition by removing or reducing naphthalenes and sulfur from CAF is also being considered as a strategy to help reduce air transportation's non-CO_2 impacts. Although current refining technologies can optimize fuel composition for environmental benefits (i.e., hydrotreating, extractive distillation), producers and suppliers have little incentive given the associated added costs. Further economic, technological, and environmental assessments are required to determine optimal and feasible solutions including policy incentives. Lastly, whilenot addressed here, the non-negligible air quality and health benefits associated with reductions in particulate emissions must also be consideredThe climate and air quality effects of non-CO_2 emissions from air transportation are largely determined by the geographic location and time of day/year that they are emitted, as well as the state of the background atmosphere (i.e., meteorology and concentration of other chemical compounds), and are therefore highly variable in space and time. Since the scaling up of SAF production is slow, studies suggest that implementing strategic mitigation plans could be a means to maximize the non-CO_2 environmental benefits in the interim. For example, targeting a few, limited flight routes that have the highest contrail warming potential based on geographic region (e.g., Europe, US and the North Atlantic region), time of year (i.e., winter), and time of day (e.g., late afternoon) for higher SAF blend usage could be an effective way to optimize the climate co-benefits of SAF. Similarly, targeting specific airports in highly polluted regions could be a way to minimize adverse impacts on air quality effectively. However, there are significant and costly logistical and infrastructural issues and challenges (e.g., separate fuel storage and handling at airports and along the supply chain) need to be addressed in determining the feasibility of such strategies.

Mitigating non-CO_2 effects is complicated by complex interdependent processes and tradeoffs, as well as scientific uncertainties associated with some of the related processes. Additionally, strategies often require overcoming numerous infrastructural and economic challenges. An industry-wide approach built on multi-stakeholder and scientific collaboration is needed to find achievable smart solutions. These solutions should also consider environmental and technological changes over the next couple of decades. Changes in the background state of the atmosphere due to reductions in surface emissions from other sectors, as well as changes in the climate, will have an influence on the effects of non-CO_2 emissions. Furthermore, with fleet turnover, low soot-producing engines will eventually replace the non-CO_2 benefits of fuel with lower aromatic content. The question arises as to whether fleet turnover will outpace the time it takes to implement and reap the environmental benefits of new fuel standards for maximum aromatic content. Given the high cost and challenges, as well as the potential role of vPM in contrail formation in the low-soot regime, priority may be given to desulfurizing jet fuel.

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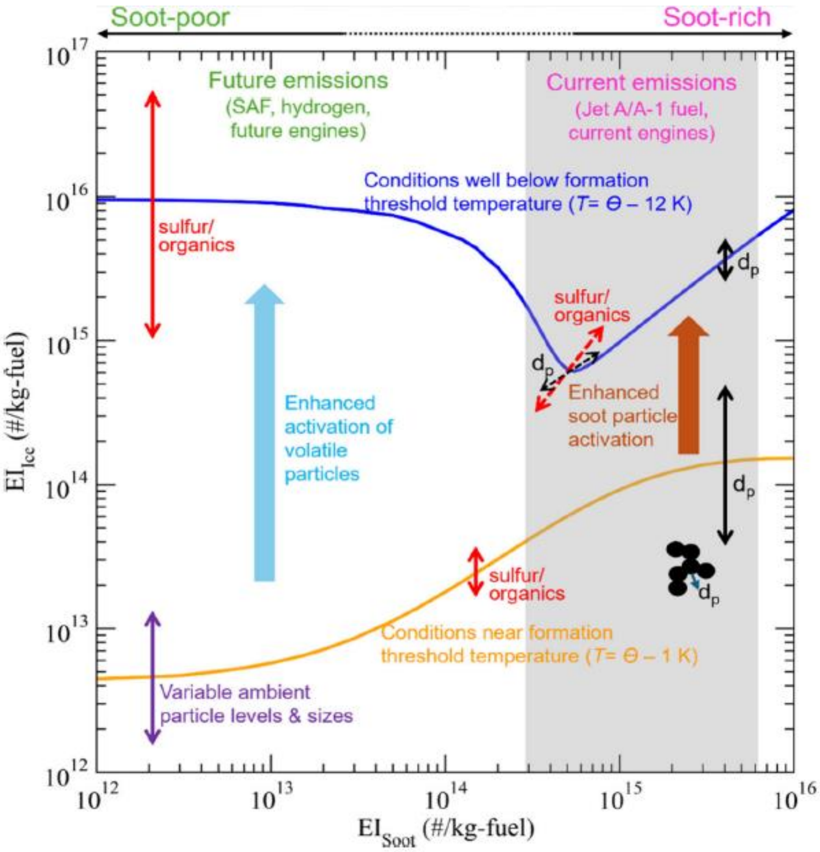
6. Appendix A: Theory on the relationship between aircraft particulate matter emissions and contrail ice crystal concentration

The theoretical relationship between the number of emitted soot particles and initial ice crystal number concentrations is well summarized in Figure A1 from Yu et al. (2024).

Figure A1: Dependency of nucleated contrail ice crystal numbers as a function of soot particle emissions (EI_{soot}), ambient temperature (T), diameters of primary soot particles (dp), fuel sulfur and concentrations of condensable organics (sulfur/organics) based on a process model.[8] In soot-rich regime, ice crystal and soot particle numbers decrease nearly in proportion. In soot-poor regime, at temperatures well below the contrail formation threshold (upper curve), ice crystal numbers increase due to water activation and subsequent freezing of vPM.



Source: Yu, F., Kärcher, B. and Anderson, B.E. (2024). "Revisiting Contrail Ice Formation: Impact of Primary Soot Particle Sizes and Contribution of Volatile Particles". *Environmental Science & Technology*. doi:https://doi.org/10.1021/acs.est.4c04340.

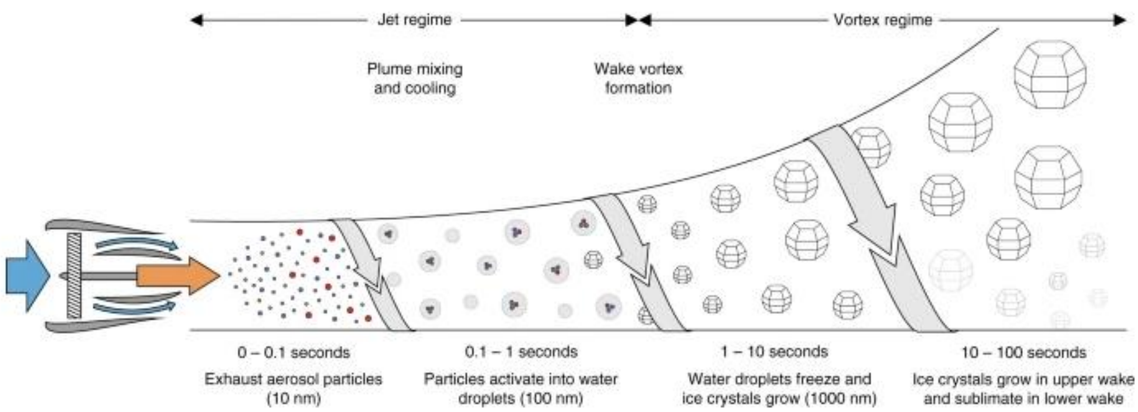
The soot emission index (EI_{soot}) of an aircraft engine depends on the type and composition of the fuel and the combustion process. Most of today's aircraft engines burning conventional kerosene jet fuel emit a large number of soot particles (> 10^{14} per kg of burnt fuel), which serve as the primary nucleation sites for water vapor to condense on and freeze, creating the ice crystals that form contrails. In this so-called "soot-rich" regime, the number of ice crystals is nearly proportional to the number of emitted particles (Kärcher et al.,

[8] **Yu, F., Kärcher B. and Anderson, B.E. (2024). "Revisiting Contrail Ice Formation: Impact of Primary Soot Particle Sizes and Contribution of Volatile Particles".** ***Environmental Science & Technology*****. doi:https://doi.org/10.1021/acs.est.4c04340.**

2018). When the ambient temperature is much colder than the temperature at which contrails start to form, nearly all the soot particles form ice crystals.

As the exhaust plume cools rapidly when mixing with the cold ambient air, it becomes water-saturated and water vapor, mainly from the exhaust, condenses onto aerosol present in the plume, forming liquid water droplets (Figure A2). These aerosols are comprised largely of soot, volatile particulate matter (vPM), which can consist of sulfuric acid, lubrication oil, and organic compounds, and entrained ambient particles (Kärcher et al., 2018). The vPM emitted from the engine has mean diameters of only a few nanometers (nm). These particles typically activate only at higher levels of supersaturation (RH > 140%), and/or in the "soot-poor" regime, where reduced soot particle concentration limits water vapor uptake and allows the plume to achieve higher supersaturation levels. Soot particles, on the other hand, have larger diameters (tens of nm) and require lower levels of supersaturation to become activated for water vapor to condense on their surfaces. In a soot-rich regime, the higher level of supersaturation required for the water activation of vPM is rarely reached because water droplets first form on soot particles, preventing supersaturation levels from getting high enough for their activation.

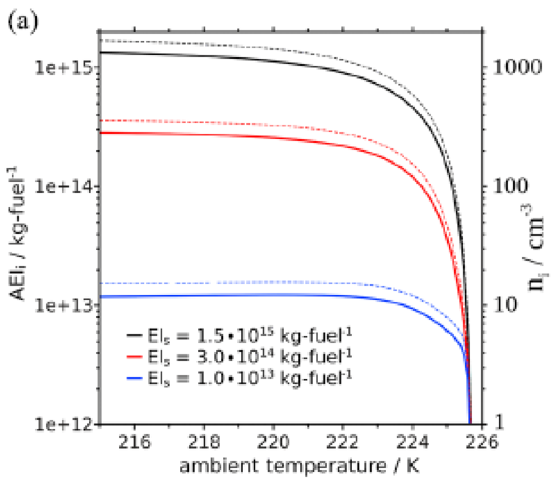
Figure A2: Processes influencing the contrail formation at different stages.



Source: Kärcher et al. (2018).

The contrail formation temperature threshold, i.e., the maximum temperature at which a contrail can form, is dependent on the fuel properties including the water vapor emission index (EI_{H2O}) and the lower heating value, the overall engine efficiency, and on ambient pressure and humidity. When the ambient temperature is close to the threshold temperature, the formation of ice crystals is limited because the low plume supersaturation (~ 100% relative humidity) limits the activation of water on soot particles, resulting in fewer ice crystals being formed. At ambient temperatures below the threshold, a higher level of supersaturation is reached, and more aerosols become water-activated. The nucleation efficiency, which describes the fraction of soot particles that get water-activated, depends nonlinearly on the difference between the ambient temperature and contrail formation temperature threshold. This can be seen in Figure A3 which has been taken from a study that used a global climate model to investigate the dependency of the apparent emission index of ice (AEI_i) on the ambient temperature for three different EI_{soot} scenarios (Bier and Burkhardt, 2022). As the ambient temperature decreases further from the contrail formation temperature threshold (~225.5 K), the number of nucleated ice crystals increases non-linearly for all three cases. Note that at maximum plume saturation (RH = 120%), 50% of the soot particles have activated in the soot-rich regime compared to 65% in the poor-soot regime. This suggests that methods that reduce soot particle emissions for contrail climate impact mitigation are more effective in colder regions where ambient temperatures are well below the contrail formation saturation threshold.

Figure A3: Dependency of the apparent emission index of ice (AEI_i) on the ambient temperature for three different EI_{soot} scenarios



Source: Bier and Burkhardt (2019).

The graph in Figure A1 depicts two lines: The lower yellow line represents conditions near the contrail formation temperature threshold and the upper blue line represents conditions well below this threshold (-12 K). When the ambient temperature is near the threshold (yellow line), the number of ice crystals formed in a contrail decreases with EI_{soot} until tapering off near a value that is close to the concentration of ambient aerosol (~10^{13} soot particles per kg of fuel). This is not the case for ambient temperatures below the threshold. The relationship is linear in the soot-rich regime for conditions well below the threshold, but when EI_{soot} drops below about 10^{14} to 10^{15} kg^{-1}, the number of ice crystals formed in the contrail may increase, depending on the ambient temperature, as the vPM may activate to form contrail ice crystals (Figure A1). This effect could have implications for the use of SAF and newer aircraft engine technologies that already emit less soot (e.g., lean burn combustors) which could, under certain conditions, produce contrails with more ice crystals than those formed by conventional rich-burn combustors and CAF. If the formation of vPM from condensable vapors in the exhaust cannot be reduced, ice crystal numbers are likely to be lowest between 10^{14} - 10^{15} particles per kg of fuel. This highlights the complexities and need for informed, strategic mitigation strategies to minimize ice crystal concentrations derived from aircraft particulate matter emissions.