D1.3 In-flight measurements in low-soot regime

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In-flight measurements with RQL and lean-burn engines using fossil jet fuel and SAF

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About the document

This deliverable analyses in-flight measurements of aerosol and contrail ice particles from modern aircraft engines. It synthesises data from the ECLIF3, NEOFUELS/VOLCAN, and ecoDemonstrator projects to assess the influence of combustion technology and fuel composition on exhaust aerosols and contrail formation. The results support contrail model development within Task T1.4.

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Nature of the deliverable [1]

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Abbreviations

(A)EI	(Apparent) Emission index
ECLIF	Emission and CLimate Impact of alternative Fuels
nvPM	Non-volatile particulate matter
RHi	Relative humidity over ice
RQL	Rich-quench-lean
SAF	Sustainable aviation fuel
tPM	Total particulate matter
VOLCAN	Compatibilité et Vol Carburants Alternatifs Nouveaux
vPM	Volatile particulate matter

Executive summary

Aviation contributes to global anthropogenic radiative forcing through both carbon dioxide (CO_2) emissions and non-CO_2 effects, of which contrail cirrus is currently one of the most significant contributors to effective radiative forcing. The climate impact of contrails depends strongly on the number of ice crystals formed in the aircraft exhaust plume, which in turn is controlled by the number and type of aerosol particles emitted by aircraft engines.
This report evaluates in-flight measurements of aerosol and contrail ice particle emissions from three in-flight measurement campaigns of aircraft emissions and contrails:

- **ECLIF3**, investigating a modern rich-quench-lean (RQL) engine operated with conventional and 100% sustainable aviation fuel (SAF),
- **NEOFUELS/VOLCAN**, providing the first in-flight dataset from lean-burn engines, burning conventional Jet A-1 and SAF,
- **EcoDemonstrator Project**, investigating brand-new lean-burn engines and quasi-sulfur free fuels

The primary objective of this work package was to analyse existing in-flight measurements of ambient aerosol, non-volatile particulate matter (nvPM), volatile particulate matter (vPM), and total particulate matter (tPM) particle emission indices, and to evaluate their applicability for contrail modelling (Output T1.4).
The combined analysis confirms two different regimes of contrail formation:

1. **Soot-rich regime (RQL engines)**
   For modern RQL combustors, contrail ice particle number scales approximately with soot (nvPM) emission index. Increasing fuel hydrogen content and reducing aromatic fraction reduces soot formation and lead to measurable reductions in contrail ice crystal number.
2. **Soot-poor regime (lean-burn engines)**
   For staged lean-burn combustors, soot emissions are reduced by up to three orders of magnitude. However, contrail ice particle numbers remain high because volatile particles formed from fuel sulfur species, organic vapours, and lubrication oil emissions act as alternative cloud nuclei. In this regime, total particle emissions correlate more strongly with ice number than soot emissions alone.

Fuel composition plays different roles in the two regimes. Hydrogen mass fraction primarily controls soot formation in RQL engines, whereas sulfur content significantly modulates volatile particle formation and contrail ice numbers in lean-burn engines. Even ultra-low-soot engines can produce substantial contrail ice crystal numbers when volatile particle nucleation pathways are active.
The findings demonstrate that a universal linear relationship between nvPM emission index and contrail ice number is not valid across all engine technologies. Contrail models must therefore incorporate regime-dependent activation schemes that distinguish between soot-controlled and volatile-controlled nucleation pathways.
Datasets from the measurement campaigns are now available for evaluation and refinement of contrail models within Task T1.4.
Overall, this work provides a comprehensive observational basis for improving the representation of aerosol-driven contrail formation in model simulations and highlights the importance of considering both combustion technology and fuel composition when assessing aviation's non-CO_2 climate impacts. Related data and evaluations are published in Dischl *et al.* (2024, 2025, 2026); Märkl (2024); Märkl *et al.* (2024); Voigt *et al.* (2025, 2026); Dischl (2026).

1. Introduction

Aviation contributes to anthropogenic radiative forcing through both carbon dioxide (CO_2) emissions and non-CO_2 effects. While CO_2 remains an important contributor due to its atmospheric lifetime, non-CO_2 effects from aircraft, involving nitrogen oxides (NO_x), water vapour, aerosols, and contrail cirrus, contribute substantially to aviation's current effective radiative forcing. In particular, contrail cirrus is estimated to contribute a radiative forcing comparable in magnitude to that of cumulative aviation CO_2 emissions over recent decades.

Unlike CO_2, contrail cirrus forms and dissipates on timescales of hours, which implies that mitigation of contrail formation could provide relatively rapid climate benefits. However, predicting contrail climate impact remains challenging, primarily because contrail formation depends sensitively on microphysical processes within the expanding aircraft exhaust plume. Central to these processes is the number and properties of particles in the aircraft exhaust plume.

Contrails form when hot, moist exhaust gases mix with cold ambient air at cruise altitude. Under sufficiently low temperatures and ice-supersaturated conditions, water vapour condenses and freezes onto available aerosol particles, forming ice crystals. The initial number of ice crystals in a contrail strongly influences its optical depth, lifetime, and radiative properties. Therefore, understanding and quantifying particle emissions from aircraft engines is a prerequisite for reliable contrail modelling.

Modern aircraft engines emit both non-volatile particulate matter (nvPM), commonly referred to as soot, and volatile particulate matter (vPM), which forms in the cooling exhaust plume through nucleation of sulfuric acid and organic vapours. For conventional rich-quench-lean (RQL) combustors, soot particles with sizes of about 30 nm are known to act as the primary ice nuclei in the young contrail. Consequently, contrail ice particle number has often been parameterised as a function of soot emission index.

However, recent advances in engine technology and the growing adoption of alternative and sustainable aviation fuels challenge this relationship. Sustainable aviation fuels (SAFs) with reduced aromatic content and higher hydrogen mass fraction can significantly reduce soot emissions. In parallel, ground experiments showed that the design of modern staged lean-burn combustors reduces NO_x and soot emissions by promoting more homogeneous fuel–air mixing and lean combustion conditions. These developments raise fundamental questions:

- What is the relationship between soot emissions and the fuel hydrogen content?
- What happens to the relationship between soot particle and contrail ice crystal numbers at very low soot emission levels?
- What role do volatile particles play when soot emissions become very low?
- Which parameters are most relevant for inclusion in next-generation contrail models?

Addressing these questions requires high-quality in-flight measurements of aerosol and contrail properties under realistic cruise conditions. Laboratory experiments and ground-based certification data are insufficient to capture the full complexity of plume microphysics and ambient interactions in the upper troposphere. Therefore, coordinated flight campaigns are essential to provide observational constraints for model development and evaluation.

The present work evaluates and summarises existing in-flight datasets obtained within three major collaborative projects:

1) ECLIF3, investigating soot and contrail formation from a modern RQL engine burning conventional and 100% sustainable aviation fuel, with a particular focus on the dependence of soot emissions on fuel hydrogen content (Dischl *et al.*, 2024, 2025; Märkl *et al.*, 2024).
2) NEOFUELS/VOLCAN, providing the first in-flight measurements of aerosol and contrail properties behind modern lean-burn engines, thereby investigating the soot-poor regime (Märkl, 2024; Voigt *et al.*, 2025, 2026; Dischl *et al.*, 2026).
3) EcoDemonstrator Project, investigating brand-new lean-burn engines and quasi-sulfur free fuels and providing new mid-field contrail data.

Together, these campaigns span both high-soot (RQL) and low-soot (lean-burn) combustion regimes and cover a wide range of fuel compositions, including variations in hydrogen, aromatic, and sulfur content.

Within this work package, the primary objective is to analyse existing in-flight measurements of ambient aerosol, nvPM, vPM, and tPM number emission indices, and to evaluate their applicability for use in contrail formation models (Output T1.4). Particular emphasis is placed on:

- The dependence of soot emissions on fuel hydrogen content,
- The relationship between soot and contrail ice particle number
- The role of volatile particles in the soot-poor regime,
- The identification of model-relevant parameters for improved contrail microphysics representation.

By integrating observational results across combustion technologies and fuel types, this report provides a consolidated data basis for refining contrail parameterisations and reducing uncertainty in aviation climate impact assessments.

2. Methods and data processing

2.1. Measurement strategy and flight configurations

The datasets analysed in this report originate from coordinated in-flight measurement campaigns in which a research aircraft probed the exhaust plumes and contrails of a source aircraft under controlled cruise conditions (Dischl *et al.*, 2024; Märkl *et al.*, 2024; Voigt *et al.*, 2025, 2026). Although the specific aircraft and engine types differed between ECLIF3, NEOFUELS/VOLCAN, and the ecoDemonstrator project, the general measurement concept was comparable.

In all campaigns, the research aircraft entered the exhaust plume at defined distances behind the source aircraft. Two sampling regimes were distinguished:

1) Near-field plume sampling, typically within 0.5-2 seconds after emission, used to determine particle and trace gas emission indices in ice-free conditions.

2) Mid- to far-field contrail sampling, performed several kilometres downstream in ice-supersaturated conditions, mainly used to determine apparent contrail ice particle emission indices.

The sampling strategy ensured repeated plume encounters under quasi-stationary engine operating conditions. Cruise Mach number, altitude, and combustor inlet temperature (or equivalent thrust setting) were kept as constant as operationally feasible to allow comparability between fuel types and combustion modes.

Ambient temperature, pressure, and relative humidity over ice (RHi) were measured simultaneously, since contrail formation and persistence strongly depend on atmospheric conditions.

2.2. Non-volatile and total particle number concentrations

Particle number concentrations were measured using condensation particle counters (CPCs) with defined lower size cut-offs. Total particle concentrations (>5 nm diameter) include both volatile and non-volatile particles. Non-volatile particle concentrations (>14 nm diameter) were measured downstream of a thermodenuder heated to remove volatile components, thereby isolating soot particles (nvPM). In this report, the non-volatile particle emission index (EI_{nv}) is interpreted as representing soot particle number emissions, since soot dominates the non-volatile fraction in the relevant size range. Total particle emission indices (EI_t) represent the sum of soot and volatile particles and are particularly relevant in the soot-poor regime, where volatile particle formation becomes significant. The number of volatile particles is determined by subtracting nvPM numbers from tPM numbers. Measurement uncertainties in particle number concentrations arise from counting statistics, pressure-dependent detection efficiency, dilution corrections, and background deviations. Typical relative uncertainties in near-field particle emission indices are on the order of ~10–15%, depending on plume signal strength and background stability.

2.3. Contrail ice particle measurements

Contrail ice particle number concentrations were measured using optical cloud and aerosol spectrometers capable of detecting particles in the sub-micrometre to tens of micrometre range. Ice particle size distributions were derived from forward light scattering measurements.

Apparent ice particle number emission indices (AEI_{ice}) were calculated analogously to particle emission indices in the near field, but using ice particle concentrations measured in persistent contrails several kilometres downstream. Only plume encounters showing clear correlation between ice particle concentration and CO_2 enhancement were considered for evaluation.

Uncertainties in AEI_{ice} are larger than for near-field aerosol measurements, due to larger plume dilution variability, ice crystal growth and sedimentation effects, instrument coincidence corrections, and larger background variability in ambient cirrus conditions. In total, the ice particle number concentrations show an uncertainty of approximately 20% (Dischl *et al.*, 2024).

2.4. Emission index calculation

To account for inhomogeneities in the plume and mixing of exhaust air with ambient air, particle concentrations are analysed using the emission index (EI). Since contrail ice particles are not directly emitted by the engines, but develop subsequently in the exhaust plume, the term apparent ice particle emission index (AEI) is used for ice particle data. CO_2 measurements were used as a tracer to calculate the emission indices to scale aerosol and ice particle numbers to the amount of fuel burned, providing a dilution-independent measure of emission:

$$(\mathrm{A})\mathrm{EI} = \frac{RT}{p} \cdot \frac{\Delta N}{(M(\mathrm{C}) + \alpha M(\mathrm{H})) \cdot \Delta \mathrm{CO_2}}$$

where R is the ideal gas constant, T and p are standard temperature (273.15 K) and pressure (1013.25 hPa), α is the hydrogen-to-carbon molar ratio of the fuel, M(C) and M(H) are the molar masses of carbon and hydrogen, ΔCO_2 and ΔN are the background-subtracted peak areas of the recorded concentrations of CO_2 and (ice) particles at standard conditions during a plume encounter sequence. The emissions index has the unit number of (ice) particles per kg of fuel burned.

This approach assumes homogeneous mixing of exhaust species within the sampled plume cross-section. For near-field measurements, concentration enhancements were determined from repeated plume intercepts at similar engine settings. For contrail measurements, only plume encounters with strong correlation between ice particle number and CO_2 were retained to ensure reliable attribution. Due to the strong signal enhancements observed in trace gases and aerosol concentrations during near-field plume encounters, the particle measurement uncertainty is the dominant contributor to the absolute uncertainty, resulting in a ΔEI of about 10%. In the far field, plume signals are more diluted and less distinguishable from the background, resulting in a higher mean ΔEI of 18%, occasionally reaching up to 30%, but remaining well below the magnitude of the observed effects. The uncertainty of the AEI amounts to 24–33% (Märkl *et al.*, 2024).

2.5. Data selection for model evaluation

The analysed datasets were filtered according to the following criteria:

- Stable cruise engine operation,
- Clearly identifiable plume intercepts,
- Reliable background determination,
- Ice-supersaturated ambient conditions for contrail analysis if possible
- Sufficient signal-to-noise ratio in particle and trace gas measurements.

Near-field emission indices were paired with contrail ice emission indices obtained under comparable engine settings and fuel types. Where direct simultaneous measurement was not possible, near-field emission data from identical operating conditions were used.

The resulting datasets provide:

1) nvPM and tPM emission indices from near-field measurements
2) Contrail ice particle emission indices from far-field and mid-field measurements,
3) Associated ambient conditions from the measurement aircraft basic data system,

Fuel compositions are given in this report. The datasets provide the basis for the results shown in the subsequent sections.

3. Results

3.1. ECLIF3: In-flight measurements of aerosols and contrail ice particles from RQL engines

3.1.1. Overview of the ECLIF3 campaign

The Emission and CLimate Impact of alternative Fuels (ECLIF) series builds upon earlier campaigns, ACCESS & ECLIF1 (2015) (Moore *et al.*, 2017) and ECLIF2/NDMAX (2018) (Voigt *et al.*, 2021), which investigated the effects of blending sustainable aviation fuels (SAF) with conventional jet fuel on emissions and contrail formation.

The successor flight experiment campaign ECLIF3, conducted in April 2021 (ECLIF3-1) and November 2021 (ECLIF3-2), for the first time allowed the investigation of effects from burning 100 % HEFA-SPK on trace gas and particle emissions as well as contrail ice formation from a large commercial passenger aircraft equipped with modern RQL engines. The aim of the ECLIF3 flight experiments was to characterize the influence of the combustion of different jet fuels and different engine power settings on soot particles, contrail ice particles, and trace gas emissions (Dischl *et al.*, 2024; Harlass *et al.*, 2024; Märkl *et al.*, 2024).

Measurement data were collected during nine research flights conducted in extended racetrack patterns in restricted airspaces over the Mediterranean Sea and off the Atlantic coast west of Bordeaux. An Airbus A350-941, equipped with Rolls-Royce Trent XWB-84 engines and operated by Airbus, served as the source aircraft. Fuel was supplied selectively from the two wing fuel tanks. This configuration allowed in-flight switching between two fuels. Since the engines could be fed from separate tanks, test points with different fuels could be accomplished within a single flight to ensure comparable atmospheric and engine conditions. For operational reasons, the right engine (engine serial number 21004) was replaced by another engine of the same type (engine serial number 21012) between April and November 2021.

In situ in-flight measurements were performed with the DLR-operated Dassault Falcon 20-E5 (registration D-CMET), which followed the emission source aircraft to measure exhaust gases, volatile and non-volatile aerosol particles, and contrail ice particles in the plume. Two distance regimes were examined. Near-field measurements probed emissions at ages of 0.5–2 seconds at distances of approximately 100–200 m behind the A350. These measurements were performed in test areas with comparatively high ambient air temperatures and low humidities preventing the formation of contrail ice particles, allowing the characterization of unprocessed emissions. The right engine was studied and operated at typical cruise combustor inlet temperature (T30), while the other engine was operated at variable thrust to keep the airspeed of the A350 within the Falcon's performance range. Near-field measurements were taken directly behind the right engine to exclusively capture its emissions. Dedicated flight test instrumentation on the A350 permitted the targeting of specific combustor inlet temperatures (T30). Engine conditions were kept constant during individual measurement sequences. Each test point, defined by the engine power setting and the fuel burned by the engine, was repeated 5 times, where one plume encounter lasted about 45 seconds, followed by a background measurement sequence. Far-field measurements were performed at distances greater than 5 NM, probing contrails aged from about 1 min to several minutes. Here, each test point was investigated for approximately 20 minutes.

Three different jet fuels were investigated during ECLIF3, see Tab. 1. A conventional Jet A-1 supplied by TotalEnergies to Toulouse–Blagnac Airport served as the reference fuel. A 100 % HEFA-SPK SAF produced by Neste Corporation was investigated during both mission phases, and a 38 % blend of HEFA-SPK and Jet A-1 was additionally sampled during ECLIF3-2 only. The blended fuel consisted of the HEFA-SPK used in ECLIF3-2 combined with a different Jet A-1 exhibiting higher naphthalene and sulfur content. Fuel properties show that the HEFA-SPK, after logistics and at the point of use, was nearly free of aromatics compared to the Jet A-1 fuel, which itself had a lower aromatic content than the global mean. The naphthalene content in the HEFA-SPK lay below the ASTM D1840 detection limit, while the total sulfur content was higher in Jet A-1 but still about 15 times below the maximum permitted mass fraction of 0.3 %. Both HEFA-SPKs showed a high content of iso-paraffins relative to n-paraffins, a property that could slightly increase soot particle formation.

Table 1. ECLIF3: Fuel composition

Selected properties of the fuels burned by the A350 during the test sequences. Fuel properties were analysed according to ASTM standards. The carbon content refers to the difference between 100 % and hydrogen and sulfur content. Fuel samples were collected from the aircraft tank prior to the flights, see Dischl et al. *(2024). World average fuel data were obtained from the CRC World Fuel Sampling Program (Hadaller and Johnson, 2006)*

Fuel	ECLIF3-1 Jet A-1	ECLIF3-1 HEFA-SPK	ECLIF3-2 Jet A-1	ECLIF3-2 HEFA-SPK	ECLIF3-2 blend	Jet A-1 world average
Hydrogen content (mass %) (ASTM D3701)	14.08	15.11	14.25	15.18	14.39	13.89
Carbon content (mass %)	85.90	84.89	85.74	84.82	85.56	NA
Sulfur content (mass %) (ASTM D5453)	0.0211	0.0007	0.0125	0.0003	0.0505	0.0460
Naphthalene content (vol %) (ASTM D1840)	0.35	< 0.08	0.50	< 0.08	0.58	1.2
Aromatics (vol %) (ASTM D6379)	13.4	NA	13.4	< 0.1	10.8	19.2

Contrail measurements in supersaturated conditions were mainly obtained during ECLIF3-1, while most flights in ECLIF3-2 were performed in slightly subsaturated conditions. In particular, the flight on 16 April 2021 over the Mediterranean Sea provided contrail data under ice-supersaturated conditions in a narrow range of atmospheric ambient and engine conditions as well as contrail ages, providing a good dataset for the comparison between conventional Jet A-1 and 100% HEFA-SPK. During this flight, racetrack patterns were flown in a north–south direction west of Corsica and Sardinia at flight level FL350 (≈10.65 km), while burning 100 % Jet A-1 and 100 % HEFA-SPK fuels sequentially in both engines. Contrails in the wake vortex phase were subsequently probed in the range of 48 m below to 96 m above the emission altitude in the secondary wake by the ice crystal instrumentation on board the Falcon.

3.1.2. Aerosol emissions from RQL engines and fuel dependence

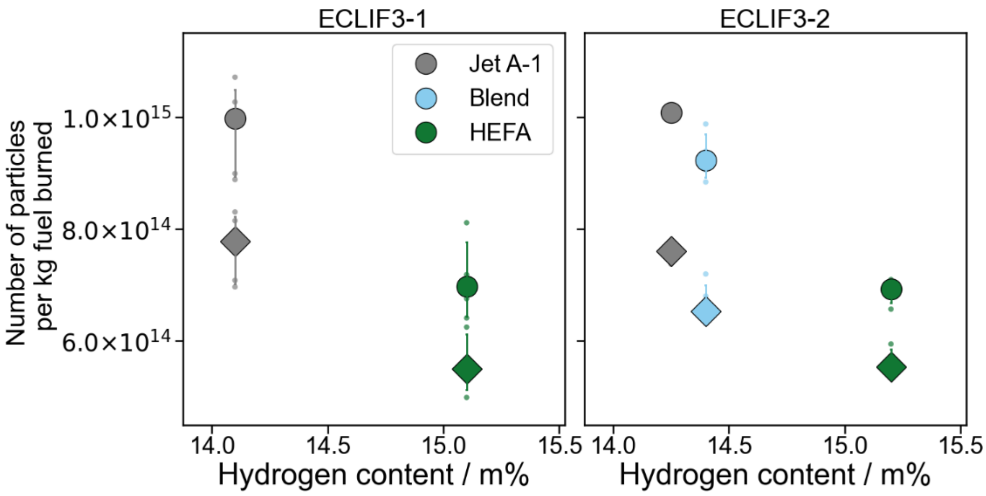

Figure 1: Emission index of non-volatile particulate matter (diamonds) and total particles (circles) with fuel hydrogen content. The figure shows median values and 25th–75th percentiles. In order to improve comparability and enhance the quality of the dataset, only measurement points at FL280 (ECLIF3-1) and FL310 (ECLIF3-2) at medium combustor inlet temperatures are shown. Emissions increase with decreasing hydrogen content. The aromatic content contributes to the formation of nvPM. The blended fuel had the highest sulfur and naphthalene content (from Dischl et al.*, (2024)).*

One major focus of ECLIF3 was investigating how fuel composition influences particle emissions, particularly soot (nvPM) produced by rich-quench-lean (RQL) engine combustion. RQL combustion systems, typical for modern high-bypass turbofan engines, produce a relatively low number of soot particles compared to older engine types, but emissions remain significant for contrail formation.

A central result of the campaign was obtained by comparing emissions from the Airbus A350 when burning 100 % HEFA-SPK against conventional Jet A-1 fuel. HEFA-SPK is representative of current SAF technology, characterized by low aromatic and sulfur content and higher hydrogen content relative to Jet A-1.

Non-volatile particle number emissions (nvPM):

Using 100 % HEFA-SPK resulted in a significant reduction of nvPM emissions relative to Jet A-1 across cruise power settings:

- At low cruise engine power: nvPM emission indices were reduced by up to 41 %.
- At typical cruise power: reductions of 29 % were observed.
- At higher cruise power settings: reductions of 22 %.

The blend fuel reduced EI_{nv} by 14% at medium power settings compared to the reference Jet A-1. These results demonstrate reduced soot formation for fuels characterized by lower aromatics and higher hydrogen contents, see Fig. 1. Additionally, nvPM particle sizes tended to be smaller for HEFA-SPK relative to Jet A-1, further affecting contrail formation potential.

The measured nvPM reductions are consistent with correlations previously found between fuel hydrogen content and particulate emissions: fuels with higher hydrogen content generally produce less soot per kilogram of fuel burned, because hydrogen-rich paraffins produce fewer soot precursors than hydrogen-poor aromatics. The results suggest that hydrogen content could be a promising predictor of nvPM production across a range of fuel types.

3.1.3. Contrail ice particle numbers and correlation to soot

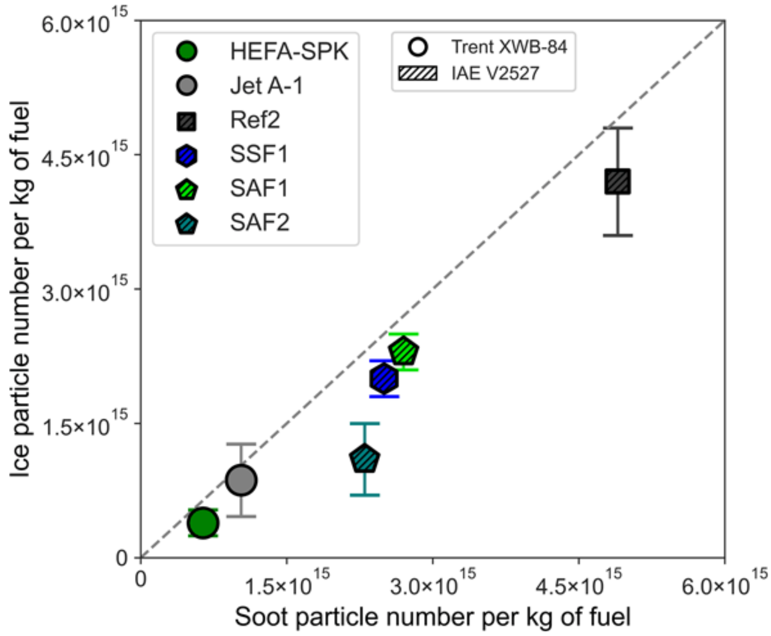

Figure 2: Apparent ice emission indices versus nvPM emission indices for Jet A-1 and HEFA-SPK fuel from the ECLIF3 campaign using a Rolls-Royce Trent XWB-84 engine (circles) compared to fuels investigated during ECLIF1 and ECLIF2/NDMAX (Ref2, SSF1, SAF1, SAF2) using an IAE V2527 engine (hatched symbols) (Voigt et al.*, 2021). The symbols represent means of the respective quantities in order to facilitate comparability between ECLIF1, ECLIF2/NDMAX, and ECLIF3 data. The dashed line shows the ideal 1 : 1 relationship between the AEI_{ice} and EI_{nv}. (from Märkl* et al. *(2024))*

Further ECLIF3 analysis focused on contrail ice particle emissions and their dependence on soot emissions and fuel composition.

The measurements provide the first in-flight in-situ observations of contrails from the combustion of 100% HEFA-SPK and showed that contrail ice particle number concentrations were substantially reduced by 56% when HEFA-SPK was burned compared to Jet A-1, see Fig. 2.

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This observation is consistent with the assumption that engine-emitted soot particles provide the primary nuclei for ice formation in young contrails. A reduction in nvPM through the use of SAF therefore directly decreases the number of available cloud condensation nuclei for RQL engines, resulting in lower contrail ice particle numbers. The correlation between nvPM and ice particle emission indices observed in ECLIF3 supports this correlation.

3.1.4. Influence of volatile particles and fuel composition

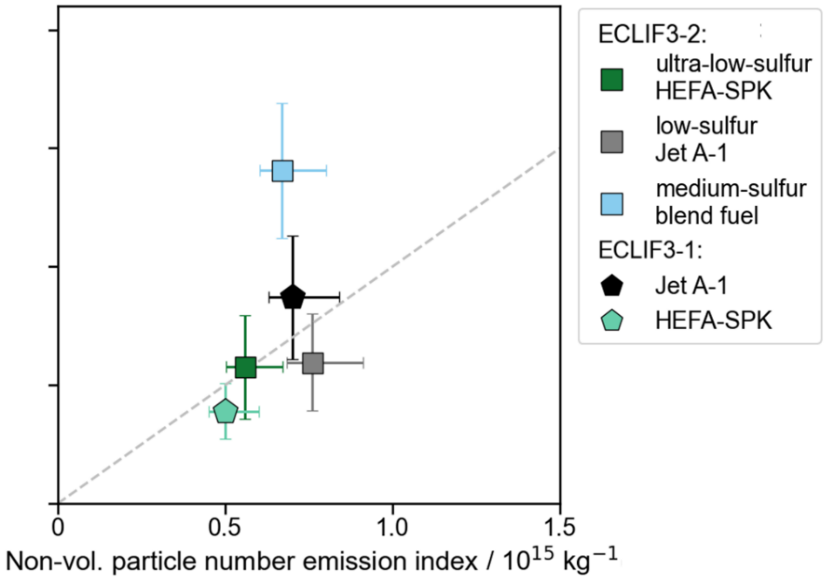

Figure 3:Mean AEI$_{ice}$ from far-field (95% < RHi < 100%) vs EI$_{nv}$ from near-field measurements (squares), including uncertainty intervals. Differences in engine and combustor operating conditions between the near and far field can result in increased nvPM emissions in the far field, as reflected by the extended error bars. Jet A-1 and HEFA-SPK test points from the earlier ECLIF3-1 campaign measured at supersaturated atmospheric conditions are shown as black and lightgreen pentagons, including uncertainty intervals. The dashed line represents the 1:1 relationship between AEI$_{ice}$ and EI$_{nv}$ (from Dischl et al.*, (2025)).*

While modern RQL engines emit fewer soot particles compared to older engine generations, the contribution of volatile particles to ice nucleation in contrails remains poorly constrained. Volatile particles form from gaseous precursors in the cooling exhaust plume and can serve as additional cloud condensation nuclei if they grow to sufficient size. Measurements indicate that the number and activation efficiency of vPM depend on fuel sulfur content, as fuels with higher sulfur levels produce more and larger volatile aerosols capable of contributing to cloud droplet formation. Other parameters, such as the release mechanism for excess engine oil, can additionally contribute organic compounds.

The results from ECLIF3 show that when nvPM emissions drop below about 10^{15} particles per kilogram fuel burned (a regime increasingly relevant for modern engine technologies), volatile aerosol activation can become more important for contrail ice formation for fuels with sufficiently high sulfur content, as for example the blend fuel tested during the campaign with a sulfur content of 505 ppm by mass. Here, volatile aerosols contribute as many condensation nuclei for contrail formation as soot particles, see Fig. 3.

Reducing the sulfur and aromatic content of fuels (as in HEFA-SPK and other alternative zero- or ultra-low sulfur fuels) limits the formation and growth of volatile and non-volatile particles, thereby suppressing their contribution to cloud condensation nuclei.

Implications for contrail modelling

The combined ECLIF3 observations: reductions in nvPM with higher hydrogen/fewer aromatic fuels and corresponding decreases in contrail ice concentrations, provide critical empirical data for contrail formation models. These datasets allow model evaluations of how fuel composition parameters (aromatic fraction, hydrogen content, sulfur content) influence particle and ice emission indices and ultimately contrail radiative forcing. Because contrail RF is strongly dependent on ice number and size distributions, the observed sensitivity to fuel properties is directly relevant for climate impact assessments and policy strategies aimed at contrail mitigation.

3.2. NEOFUELS/VOLCAN: Lean-burn engine emissions and contrail formation in the soot-poor regime

3.2.1. Project background and objectives

The NEOFUELS/VOLCAN campaign was designed to investigate particle emissions and contrail formation behind modern aircraft equipped with lean-burn combustor technology. While contrail formation behind conventional rich-quench-lean (RQL) engines has been studied extensively in previous campaigns, in-flight data for lean-burn engines at cruise altitude were largely missing prior to this project. This data gap has introduced substantial uncertainty into contrail climate impact assessments, because existing models predict largely different ice crystal numbers in the soot-poor regime.

Lean-burn combustors are designed to reduce nitrogen oxide and soot emissions by distributing fuel more homogeneously and operating with extended lean combustion zones. Certification data based on ground measurements already indicated very low soot emissions. However, theoretical studies suggested that when soot emissions become extremely low, alternative nucleation pathways involving volatile particles might dominate contrail formation. Without observational evidence, it remained unclear whether lean-burn engines would significantly reduce contrail ice crystal numbers or whether other particle types would compensate for possible soot depletion.

To address this question, the NEOFUELS/VOLCAN campaign (Voigt *et al.*, 2025, 2026) conducted dedicated in-flight measurements behind an Airbus A319 neo and A321neo equipped with CFM LEAP-1A engines. The engines could be operated both in their standard lean-burn cruise configuration and, for comparison, in a forced rich-burn mode at similar combustor inlet temperatures. This allowed a direct comparison of aerosol and contrail properties under controlled combustion conditions.

The campaign investigated conventional Jet A-1 fuel as well as several sustainable aviation fuel (SAF) blends with different sulfur and aromatic contents. Table 2 shows fuel properties of the fuels used for the results shown in Fig. 4 and 5. As during ECLIF3, the DLR Falcon research aircraft sampled near-field emissions shortly after emission in the 0.5 to 2 seconds old plume in non-contrail forming conditions and contrails several kilometres downstream under ice-supersaturated atmospheric conditions.

Table 2. NEOFUELS/VOLCAN: Fuel compositions

Fuel composition of fuels used during NEOFUELS/VOLCAN; and world average Jet A-1 composition from Hadaller and Johnson, (2006). The hydrogen content was measured by ASTM D3701 with a repeatability of 0.09 and a reproducibility of 0.11. The sulfur content was measured by ASTM D5453, with a detection limit of 1 ppm by mass. Fuel samples were taken from the refuelling truck. Further, the FSC measured in fuel samples from the aircraft after the flights are given in parenthesis. Fuel probes of Jet A-1 shown in Fig. 5 contain small amounts of HEFA fuel (5%), resulting in 192 ppm sulfur *for Jet A-1. The chemical properties of this blend are very close to pure Jet A-1 and it is referred to as Jet A-1 throughout this study (from Voigt* et al. *(2025, 2026)).*

Fuel	Fuel Components	Hydrogen content [%m/m] ASTM D3701	Carbon content [%m/m] calc. from H content	Sulfur content [ppmm] ASTM D5453	Aromatic content [%v/v] ASTM D6379	Naphthalene content [%v/v] ASTM D1840
Jet A-1	conventional Jet A-1	14.1	85.9	195 (192)	12.8	0.6
Jet A-1* world av.	world average Jet A-1	13.9	85.1	460	19.2	1.2
HEFA-SPK	100% HEFA-SPK	15.3	84.7	3	<1	<0.1
HEFA-blend	64% HEFA + 36% Jet A-1	14.8	85.2	75	4.7	0.3

3.2.2. Aerosol emissions in rich-burn and lean-burn operation

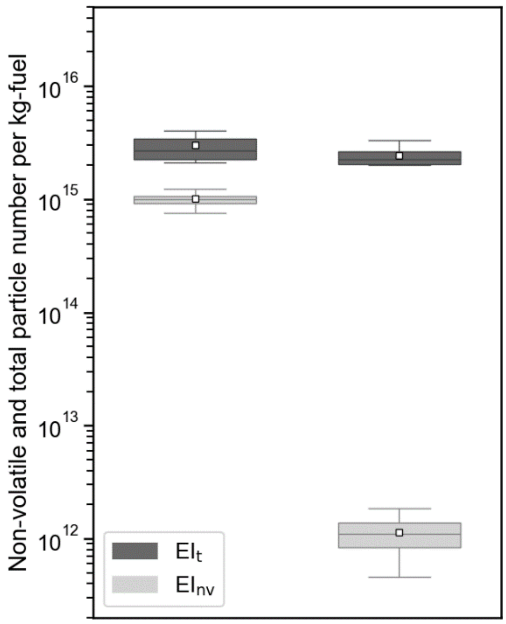

Figure 4: Emission indices of total particles (EI_t, d > 5 nm, dark grey) and non-volatile particles (EI_{nv}, d > 14 nm, light grey) emitted per kg fuel in forced rich-burn and lean-burn engine conditions for reference Jet A-1 fuel. Results show medians, 25 and 75 percentiles, minimum and maximum (from Voigt et al. *(2025, 2026)).*

The most striking difference between forced rich-burn and lean-burn combustion modes was observed in the non-volatile particle emission index, i.e.in the number of soot particles per kilogram of fuel burned, see Fig. 4:

When the LEAP-1A engines were operating in forced rich-burn mode, soot emission indices were on the order of 10^{15} particles per kilogram of fuel. These values are comparable to those measured for modern RQL engines and presumably fall within the expected range for current fleet aircraft operating at cruise. Thus, in forced rich-burn configuration, the lean-burn engine behaves similarly to other modern turbofan engines in terms of soot emissions.

In contrast, when operated in its standard lean-burn cruise mode, soot emissions were reduced by approximately three orders of magnitude. Measured non-volatile particle emission indices dropped to around 10^{11}-10^{12} particles per kilogram of fuel, approaching background level concentrations. This represents one of the lowest soot emission levels documented during in-flight measurements of a commercial aircraft engine.

From a combustion perspective, this confirms that lean-burn technology significantly suppresses soot formation. Presumably, the homogeneous fuel-air mixture and lower local fuel-rich zones effectively inhibit the formation of soot precursors and significantly limit particle growth.

However, the trend differs when considering total particle emissions. Measurements of particles larger than 5 nm show that total particle emission indices in lean-burn mode remained on the order of 10^{15} particles per kilogram of fuel. Therefore, although soot particles were strongly reduced, large numbers of volatile particles were still present in the exhaust plume.

This shift reflects a fundamental change in plume microphysics. In rich-burn operation, abundant soot particles act as a condensation sink for sulfuric acid and organic vapours formed during combustion. In lean-burn conditions, where soot is scarce, this sink is greatly reduced. As a result, sulfuric acid, organic vapours, and lubrication oil vapours can nucleate new volatile particles more efficiently and contribute to their growth, resulting in an increased numbers of volatile particles > 5nm compared to rich-burn operation.

Fuel composition further modulated these emissions. Conventional Jet A-1, with a sulfur content around 192 ppm by mass, enhanced the formation of volatile sulfate particles > 5 nm. Blends with lower sulfur content, such as the HEFA-blend (75 ppm sulfur), produced fewer volatile particles > 5 nm. Ultra-low-sulfur HEFA-SPK (3 ppm sulfur) reduced volatile particle numbers even further. Nevertheless, even at very low sulfur levels, measurable volatile particle formation persisted, indicating that organic vapours and lubrication oil emissions also contribute to particle nucleation in the soot-poor regime.

3.2.3. Contrail ice particle formation in the soot-poor regime

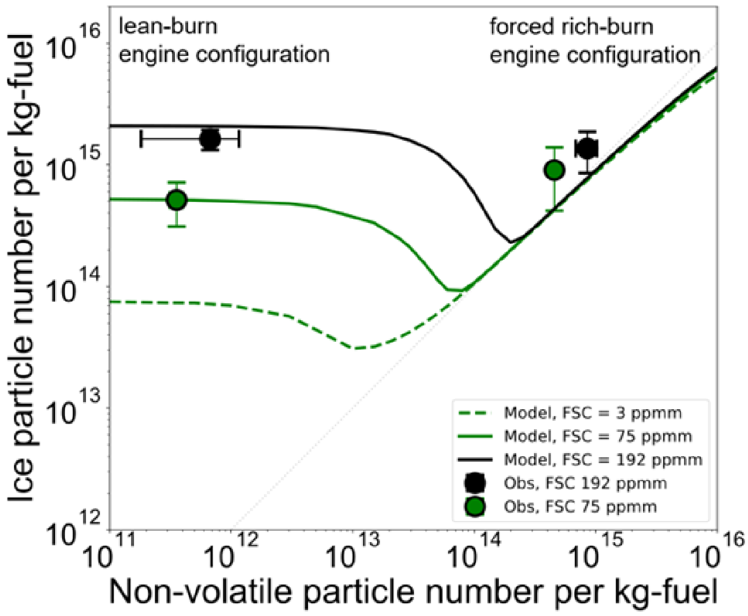

Figure 5:Dependence of contrail ice crystal numbers on combustion mode and fuel composition; Symbols show mean and arithmetic standard deviation of non-volatile (EI_{nv}, d > 14 nm), and ice (AEI_{ice}, d > 0.6 µm) particle number emissions indices measured under lean-burn and forced rich-burn combustor configurations for Jet A-1 (black) and a HEFA-blend (green) at 218 K ambient temperature. Lines denote simulations with the updated aerosol and contrail microphysics model (ACM) at comparable conditions (218 K, 10 K below TSA) for lean- and rich-burn combustion modes and three fuel composition cases (Jet A-1 with 192 ppm sulfur; HEFA-blend with 75 pm S; HEFA-SPK with 3 ppm). The grey dotted line indicates the 1:1 relationship (from Voigt et al. *(2025, 2026)).*

The contrail measurements provided the most significant findings of the campaign. Persistent contrails were sampled several kilometres downstream of the A321neo in ice-supersaturated conditions. The apparent ice particle emission index was determined analogously to particle emission indices in the near field.

For lean-burn cruise operation with Jet A-1, the measured contrail ice particle emission index was approximately 1.6×10^{15} particles per kilogram of fuel. This value is roughly three orders of magnitude higher than the corresponding soot emission index in lean-burn mode. Thus, despite soot reduction, contrail ice crystal numbers remained at levels comparable to those observed behind conventional RQL engines.

This result provides clear experimental evidence that soot particles are not the only relevant ice nuclei in the soot-poor regime. Instead, volatile particles formed within the exhaust plume must play a dominant role in initiating contrail ice formation.

Further analysis showed that ice particle numbers correlated more closely with total particle emissions than with soot emissions alone. In lean-burn mode, newly formed volatile particles, presumably primarily sulfate particles formed from fuel sulfur oxidation, along with contributions from organic vapours and lubrication oil emissions, appear to provide sufficient nuclei for ice activation.

Fuel sulfur content had a measurable influence on contrail ice numbers. When comparing Jet A-1 (192 ppm sulfur) with a HEFA-blend containing 75 ppm sulfur under similar ambient conditions, contrail ice particle numbers were reduced by approximately a factor of three for the lower-sulfur fuel. This demonstrates that sulfur-driven volatile particle formation contributes significantly to ice particle formation in the lean-burn regime. For ultra-low-sulfur fuels, further reductions were observed, although contrail ice numbers did not approach soot number concentrations.

Ambient temperature also influenced contrail ice formation. Colder conditions increased peak supersaturation in the expanding plume, enabling activation of smaller volatile particles and leading to higher ice crystal numbers.

3.2.4. Implications for contrail modelling

In the soot-rich regime typical for RQL engines, contrail ice crystal numbers scale approximately with soot emission indices. In contrast, in the soot-poor regime characteristic of lean-burn operation, volatile particle formation compensates for the soot reduction. As a consequence, contrail ice numbers remain high even when soot emissions are reduced by three orders of magnitude.

This finding has important implications for contrail modelling. Parameterisations that rely solely on non-volatile particle emission indices are insufficient to describe contrail formation for lean-burn engines. Instead, total particle emissions and fuel sulfur content must be considered. In addition, lubrication oil vapour emissions may need to be included explicitly in future modelling approaches.

The campaign demonstrates that reducing soot emissions alone does not guarantee a proportional reduction in contrail ice crystal numbers. While lean-burn technology successfully suppresses soot formation, volatile particle nucleation introduces an alternative pathway for contrail formation. Consequently, the climate impact of lean-burn engines cannot be assumed to be lower without accounting for volatile particle processes.

3.3. EcoDemonstrator Project: Emissions and contrails from brand-new lean-burn engines and zero-sulfur fuels

The ecoDemonstrator project provides the third major dataset considered within this work package. While ECLIF3 focused on a modern RQL engine and NEOFUELS/VOLCAN provided the first in-flight dataset for lean-burn combustion, the ecoDemonstrator project extends this investigation to another, brand-new state-of-the-art lean-burn engine.

In October 2023, Boeing, NASA and DLR conducted a coordinated flight and ground test campaign at Paine Field, Washington, using a Boeing 737 MAX equipped with CFM LEAP-1B engines. The NASA DC-8 research aircraft served as the chase platform to measure engine emissions and contrail properties at cruise altitude. A total of 11 joint flight tests and two ground tests were performed (Baughcum, 2024; T. Bräuer, 2024, 2024)

The ecoDemonstrator campaign was designed to investigate:

1) Particle emissions from a brand-new modern lean-burn engine (LEAP-1B),
2) Contrail ice particle formation under cruise conditions
3) The influence of ultra-low-sulfur SAF and low-sulfur Jet-A,

A central motivation of the project was to probe the soot-poor regime highlighted in theoretical studies of contrail formation. In order to minimize aerosol emissions, and thereby potentially reduce contrail ice particle numbers to the lowest levels achievable with conventional combustion engines, newly manufactured, previously unused engines and fuel tanks were operated with a SAF containing as little sulfur as possible that was compared with a low sulfur Jet A and a conventional Jet A.

3.3.1. Fuels and experimental configuration

Fuel properties were characterised in detail prior to testing, see Table 3. Compared to conventional Jet-A, SAF exhibited higher hydrogen content and substantially reduced sulfur content, consistent with trends observed in ECLIF3 and VOLCAN. The low-sulfur Jet A showed the lowest sulfur and highest aromatic content.

Near-field ground measurements were conducted to characterise nvPM emissions at different engine thrust levels. Cruise-level in-flight measurements focused on mid-field and far-field plume encounters, where, among other species, contrail ice particle number concentrations as well as total and non-volatile particle number concentrations were measured mostly in contrail forming conditions.

Table 3. EcoDemonstrator: Fuel composition

Fuel composition of fuels used during ecoDemonstrator (Baughcum, 2024; T. Bräuer, 2024). Fuel properties were characterised in detail prior to testing.

	Total aromatics	Hydrogen content	Sulfur content
Fuel	[%v/v]	[%m/m]	ppm by mass
HEFA-SPK	0.3	15.2	2.6
Low-sulfur Jet A	21.3	13.5	1.6
Conv. Jet A	17.4	13.6	786.8

3.3.2. Scientific relevance and connection to previous projects

The ecoDemonstrator project builds directly upon insights from the NEOFUELS/VOLCAN campaign. In both cases, extremely low soot emissions were observed from staged lean-burn engines. The ecoDemonstrator measurements further explore whether contrail ice particle numbers in such engines scale with soot emissions or are influenced by alternative nucleation pathways.

Preliminary analyses indicate that measured cruise-level apparent ice emission indices were lower than those typically associated with conventional RQL combustors, yet higher than would be expected based solely on ground-based nvPM measurements and certification data. This behaviour is consistent with findings from NEOFUELS/VOLCAN.

Importantly, the ecoDemonstrator campaign confirms that soot particles cannot be used to derive contrail ice particle numbers for lean-burn engines operating in the soot-poor regime. Volatile particles, originating for example from lubrication oil and sulfuric compounds, must be considered alongside soot emissions.

The dataset is now available for further scientific evaluation and future integration into emission and contrail modelling.

4. Discussion

The three campaigns analysed in this report, ECLIF3, NEOFUELS/VOLCAN, and the ecoDemonstrator project, together span a wide range of combustion technologies and fuel compositions. When considered collectively, they provide a coherent picture of how contrail formation mechanisms shift across different emission regimes.

In the **soot-rich regime** represented by modern RQL combustors (ECLIF3), contrail ice crystal numbers scale approximately with the non-volatile particle emission index, with possible dependence on the fuel sulfur content for high and low sulfur fuels. Reducing aromatic content and increasing fuel hydrogen content leads to measurable reductions in soot number emissions. The observed 56% decrease in contrail ice particle number when burning 100% HEFA-SPK compared to conventional Jet A-1 confirms the near-linear relationship between soot emissions and initial contrail ice crystal numbers under these conditions. In this regime, soot particles remain the dominant cloud condensation nuclei for contrail formation, and fuel hydrogen content acts as a primary control parameter through its influence on soot formation.

In contrast, the lean-burn regime investigated during NEOFUELS/VOLCAN reveals a fundamentally different behaviour. Here, soot emissions were reduced by approximately three orders of magnitude compared to rich-burn operation. However, contrail ice particle numbers did not decrease proportionally. Instead, apparent ice emission indices remained on the order of 10^{15} particles per kilogram of fuel, comparable to soot-rich engines. This demonstrates that when soot emissions are reduced below a certain threshold, volatile particle formation becomes the dominant pathway for contrail ice crystal formation.

The ecoDemonstrator campaign confirms these observations. Despite lower nvPM emission indices, contrail ice numbers remained substantially higher than expected from soot emissions alone, consistent with the activation of volatile particles. Across both lean-burn datasets, total particle emission indices correlated more strongly with contrail ice number than soot emissions alone.

Together, these observations indicate the existence of two distinct regimes of contrail formation:

Soot-controlled regime (high nvPM):

Contrail ice number scales primarily with soot emission index. Fuel hydrogen content and aromatic fraction influence ice number through modulations in soot number concentrations. However, for EI_{nv} below approximately 10^{15} particles per kilogram of fuel, the fuel sulfur was observed to modulate contrail ice crystal numbers for medium fuel sulfur contents.

Volatile-particle-controlled regime (low nvPM):

Contrail ice number is largely governed by newly formed volatile particles (sulfate, organics, lubrication oil-derived particles), when soot emissions are minimal.

The integrated findings from the three campaigns directly inform model development and evaluation within this work package

First, the assumption of a universal linear relationship between nvPM emission index and contrail ice number is only valid in the soot-rich regime. For lean-burn engines operating at very low soot levels, this assumption breaks down.

Second, total particle or volatile particle numbers are required to describe contrail ice formation in the soot-poor regime. Fuel sulfur content should be included as a model parameter influencing volatile particle formation rates. In addition, lubrication oil emissions may need to be represented explicitly or implicitly in advanced contrail models.

Third, hydrogen mass fraction remains a useful predictive parameter for soot emissions in RQL engines and thus for contrail formation in the soot-rich regime. However, it is not sufficient to describe contrail behaviour in lean-burn configurations.

Finally, the datasets highlight the importance of regime-aware parameterisations. Contrail models should distinguish between

- Soot-dominated activation (RQL engines, $EI_{nv} \gtrsim 10^{15}$ particles per kg fuel)
- Intermediate regime,
- Volatile-dominated activation (lean-burn, very low $EI_{nv} \lesssim 10^{13}$ particles per kg fuel)

Incorporating this regime transition into contrail parameterisations is essential to reduce uncertainty in the estimated contrail radiative forcing of future fleets. Also, further measurements are needed to investigate the intermediate regime and to further constrain the relationships between exhaust aerosol number concentrations and fuel properties.

The following parameters are identified as essential inputs for contrail microphysics models:

1) **Non-volatile particle emission index (EI_{nv})**

Required to represent soot-driven activation in soot-rich regimes.

2) **Total particle emission index (EI_t)**

Required in soot-poor regimes where volatile particles dominate ice nucleation.

3) **Fuel hydrogen content**

Serves as a predictive parameter for soot emissions in RQL engines and can be used in emission modelling.

4) **Fuel sulfur content (FSC)**

Strongly modulates volatile sulfate particle formation and must be considered in soot-poor and intermediate conditions.

5) **Combustion regime indicator (RQL vs lean-burn)**

Essential to determine whether soot- or volatile-controlled activation should be applied.

6) **Ambient thermodynamic conditions**

Temperature and relative humidity over ice determine peak supersaturation and volatile particle activation efficiency and thereby initial ice crystal numbers.

The ecoDemonstrator and VOLCAN datasets further suggest that lubrication oil emissions and volatile organic vapours may influence volatile particle formation. While explicit quantification remains uncertain, their potential contribution should be considered in advanced models.

Implications for future fleet simulations

Many current global contrail models (Burkhardt and Kärcher, 2011; Gettelman *et al.*, 2022; Teoh *et al.*, 2024) assume that lean-burn engines, due to their low soot emissions, produce proportionally fewer contrail ice crystals. The combined observational evidence from VOLCAN and ecoDemonstrator indicates that this assumption may underestimate contrail ice numbers in soot-poor regimes.

Future fleet projections involving increasing adoption of lean-burn engines and sustainable aviation fuels must therefore account for the possibility that volatile particle activation sustains contrail formation even at very low soot emission levels.

At the same time, fuel reformulation remains a viable mitigation lever. Hydrogen-rich fuels reduce soot emissions in RQL engines, while low-sulfur fuels reduce volatile particle formation in lean-burn engines. These fuel-property dependencies can be implemented in emission models using hydrogen mass fraction and sulfur content as predictive variables.

5. Conclusions

This report synthesises in-flight measurements of aerosol and contrail ice particle emissions from three major campaigns covering both modern rich-quench-lean and staged lean-burn engine technologies and a range of fuel compositions.

The combined evidence leads to the following main conclusions:

In the soot-rich regime typical of RQL engines, contrail ice particle numbers scale approximately with non-volatile particle emission index. Hydrogen-rich, low-aromatic fuels reduce soot emissions and thereby reduce contrail ice numbers.

Lean-burn combustor technology reduces soot emissions by up to three orders of magnitude compared to rich-burn operation. However, this does not lead to a proportional reduction in contrail ice particle numbers.

In the soot-poor regime, volatile particles formed from fuel sulfur species, organic vapours, and lubrication oil emissions provide alternative cloud condensation nuclei for contrail formation. Total particle emissions correlate more strongly with contrail ice number than soot emissions alone.

Fuel sulfur content significantly modulates contrail ice formation. Lower sulfur fuels reduce volatile particle formation and can decrease ice crystal numbers.

The relationship between soot emissions and contrail ice number is regime-dependent. A universal linear parameterisation is not valid across both RQL and lean-burn technologies.

Future contrail models must incorporate regime-aware activation schemes that distinguish between soot-dominated and volatile-dominated nucleation pathways.

The datasets from ECLIF3, NEOFUELS/VOLCAN, and ecoDemonstrator provide a comprehensive observational basis for improving contrail microphysics parameterisations and reducing uncertainty in aviation climate impact assessments.

Overall, the transition from the soot-rich to the soot-poor regime represents a key challenge for next-generation aircraft and contrail modelling. While technological advances and alternative and sustainable fuels offer pathways to reduce emissions, accurate representation of plume microphysics remains essential for reliable quantification of aviation's non-CO_2 climate effects.

6. Data availability

ECLIF3

The data are collected at the HALO database (doi: 10.17616/R39Q0T) at https://halo-db.pa.op.dlr.de/mission/124 and https://halo-db.pa.op.dlr.de/mission/129.

NEOFUELS/VOLCAN

The data are collected at the HALO database (doi: 10.17616/R39Q0T) at https://halo-db.pa.op.dlr.de/mission/129 and https://halo-db.pa.op.dlr.de/mission/136.

EcoDemonstrator

The data are available from the authors upon request.

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