Contrails Science in Flight

Executive Summary

In recent years, partners across industry, academia and government agencies have led major flight and ground test research campaigns to make substantial advances in our understanding of how fuel type, engine technology and atmospheric conditions impact contrail formation and persistence. These collaborative efforts demonstrate strong industry commitment and investment in non-CO_2 climate research. As a result, we have a growing, peer-reviewed evidence-base that is guiding our collective efforts to address climate change.

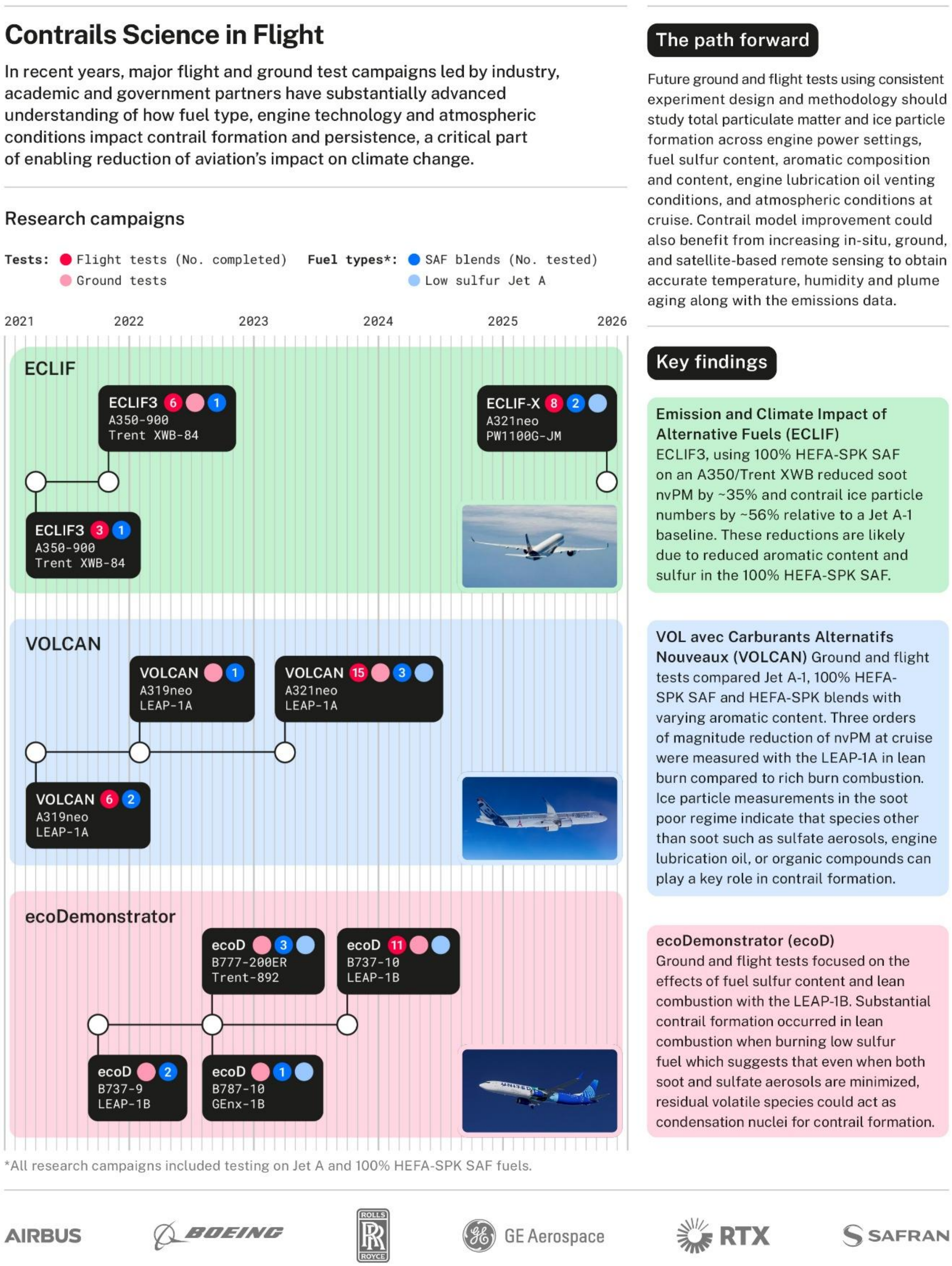
Three flight and ground test research campaigns over the past five years – ECLIF3, VOLCAN, and ecoDemonstrator – have produced the following learnings:

- **Fuel type:** Lower aromatic fuels, including HEFA-based sustainable aviation fuels (SAF), lead to reduced emitted non-volatile particulate matter (nvPM, a.k.a, soot) and lower sulfur fuels reduced emitted volatile particulate matter (vPM). Reduction of total particulate matter may lessen contrail climate impact and contrail optical thickness in flight tests.
- **Engine technology:** Aircraft engine technologies that yield very low soot emissions do not necessarily reduce contrail formation. Measurements show substantial contrail formation occurred in soot poor exhaust regime which suggests that residual volatile particulate matter species (vPM) could act as condensation nuclei for contrail formation. The make-up of nvPM and vPM in the soot poor exhaust regime and their effects in the plume requires further study.
- **Atmospheric conditions:** Small variations in upper-tropospheric temperature and relative humidity (RHi) impact contrail formation and persistence. The spatial and temporal variability of ice-supersaturated regions remain a source of uncertainty in contrail forecasts. The research conducted provided useful case studies to inform the RHi sensor technology advancements needed to improve these contrail forecasts.

These key learnings have shaped recommendations for future ground and flight test campaigns:

- **Evolve objectives with learning:** Focus research on how nvPM and vPM size distributions and composition connect to contrail ice nucleation and on collecting effective datasets for meteorological and contrail microphysics model validation.
- **Improve methods and capability:** Standardize test protocols and advance chase-plane platforms and instrumentation to produce increasingly robust, high-quality emissions and atmospheric observations.
- **Test on ground and in flight:** Vary fuel sulfur content, aromatic content and composition, engine power settings and oil venting conditions while observing emission characteristics, contrail formation and evolution. Increase and improve temperature, humidity and remote sensing measurements to capture the role of atmospheric conditions and contrail lifetime.

Significant continued research is ongoing that builds on these research campaigns and expands their scope. Together, these research programs enable two key contrail impact mitigation strategies: operational contrail avoidance and deployment of future fuel and engine technologies.



Infographic

Contrails Science in Flight

Over the past several years, key players in commercial aviation have completed major flight and ground test and measurement programs at the forefront of aviation and climate science. These programs seek to better understand the relationship between fuel type, engine technology, atmospheric conditions, aircraft emissions and aviation contrails with the ultimate goal of enabling reduction of aviation's impact on climate change.

Aviation emissions include CO_2, water vapor, nitrogen oxides (NO_x), carbon monoxide (CO), sulfur oxides (SO_x), soot particles or non-volatile particulate matter (nvPM), and liquid volatile aerosols (vPM). A key non-CO_2 effect, persistent contrails, are estimated to have a warming climate impact. A contrail is an initially line-shaped ice cloud that forms behind aircraft at cruise altitudes when exhaust water vapor condenses onto emitted aerosols and freezes into ice crystals under sufficiently cold and humid conditions. Contrails can be short-lived or persistent. Persistent contrails are those that have grown for hours and can spread to resemble natural cirrus clouds. These can affect radiative forcing and, on balance globally, are estimated to cause net warming, although with large uncertainties and strong spatial and temporal variability.

In July 2024, aerospace industry Chief Technology Officers released a joint statement calling for increased research funding and collaboration "to develop the science needed to underpin technology choices, operational changes and policy decisions" for non-CO_2 emissions. Two key priorities for this mission are to improve understanding of contrail formation, persistence, and climate impact, and to improve understanding of emissions properties. This science advancement is key to enabling more accurate contrail forecasts and analysis data sets for performing impact assessment and to support implementation of contrail climate impact mitigation strategies, operational contrail avoidance and advancing fuel and engine technology.

This report summarizes the findings of three industry-led research campaigns completed in the past five years aligned to these priorities: ECLIF3, VOLCAN, and ecoDemonstrator. Other recent and ongoing industry research efforts are summarized in the appendices.

Thanks to many researchers, including critical expertise from global climate and weather organizations, academia and government agencies involved across multiple programs, more than fifteen research publications with key findings from these programs have become available to inform the fundamentals of contrail formation and persistence as a basis for next steps on research to further understand contrail impact mitigation. The intent of this report is to offer readers a cross-program synopsis of this published research that shows the effectiveness of these major industry investments and highlights opportunities for future phases of research.

Trajectory set

These industry-led campaigns build on the learnings of decades of experimental flight and ground tests as well as established academic, government, and industry capability. Not only did data from campaigns in the 1990s through the 2010s help build datasets and models that unlocked fundamentals of contrail formation, they also provided learning for scientists on measurements, instrumentation and how to execute a successful flight test campaign. Notably, 2018 "ECLIF2 / NDMAX" research led by DLR, NASA, NRC Canada, Aerodyne Research and Missouri S&T utilized DLR and NASA test aircraft to characterize emissions from five different fuel types, establishing fundamental relationships between fuel aromatic content and type, soot emissions and contrails. See Appendix B for more information.

In the 2020s, this type of research accelerated dramatically, with the focus of this report being the ECLIF3, VOLCAN, and ecoDemonstrator research campaigns occurring between 2021 – 2025.

A Science-based Mission

Understanding the mechanisms of emissions properties and contrail formation and persistence has been a key focus of the research programs. There are three main drivers of emissions properties and contrail formation and persistence that are studied across the research campaigns: fuel type, engine technology, and atmospheric conditions.

Fuel Type
The chemical composition of fuel strongly affects engine emissions properties which impact contrail formation, persistence and optical properties. Conventional jet fuels contain sulfur and aromatic hydrocarbons, which are important sources of particulates relevant to contrail formation. Some sustainable aviation fuels (SAF) and fossil-derived fuels contain reduced levels of sulfur and/or aromatic compounds compared with conventional jet fuels. Research focuses on the role of these compounds in contrail ice crystal nucleation.

Engine Technology
Aircraft engine technology also influences emissions and contrail properties. The major combustion products, which are CO_2 and H_2O, are governed by overall fuel composition and combustor fuel-to-air ratio; specific combustion technologies do not greatly change these major products. Other combustion species, such as CO, NO_x, and particulate matter are strongly influenced by aircraft engine technologies and design choices.

Engine technology and operating conditions yield particulate emissions that can be classified into two principal engine exhaust regimes relevant to contrail formation: soot-poor and soot-rich. Non-volatile particulate matter (nvPM) is directly emitted as soot particles. Volatile particulate matter (vPM) from sulfates, nitrates, organic species, and vented engine lubrication oil also contribute to contrail formation. In the absence of the larger soot particles, the smaller particles (e.g., volatile species) become more important for ice crystal production. The scientific research focuses on the complex interactions between nvPM and vPM in the soot-poor and soot-rich exhaust regimes and their impacts on contrail formation and growth.

Atmospheric Conditions
Persistent contrails occur in certain weather regimes under specific temperature and humidity conditions. Contrails form when exhaust water vapor condenses onto aerosol particles to form liquid droplets that subsequently freeze. This requires 1) sufficiently low temperatures and high ambient relative humidity so that the exhaust plume is supersaturated with respect to liquid water for contrails to form and 2) ambient air which is supersaturated with respect to ice (RHi) for contrails to persist. Small changes in temperature or RHi can impact contrail formation and persistence making atmospheric

variability a primary driver of contrail occurrence and climate impact. Additionally, the vertical variation of the temperature and RHi affect contrail evolution. Regions where persistent contrails form, called ice supersaturated regions, can be 100m to 1000m thick and can be hard to predict. Atmospheric humidity and temperature measurements can come from ground and space-based remote sensors and in-situ sensors on aircraft. Research focuses on instrumentation and practices for accurate prediction of regions where persistent contrails will form, with particular interest in identifying the "big hit" regions where the contrails are expected to be most impactful.

Research Takes Flight

Research on the impact of fuel type, engine technology and atmospheric conditions can include lab-based work, ground-testing with more realistic engine and fuel conditions, and flight-testing which includes realistic engine, fuel, and atmospheric conditions. Due to the significant role played by the atmospheric pressure, temperature and humidity, flight testing is very high-value and critical for progressing the understanding of ice particle and contrail formation and contrail persistence.

A limited number of industry stakeholders and academic institutions have expertise and assets to execute flight testing. The ECLIF3, VOLCAN, and ecoDemonstrator programs are collaborations bringing together test aircraft, chase aircraft, specialized instrumentation and operators, and expertise on fuels, combustion, atmospheric science, and aircraft and engine operations. These programs operated over years-long periods, combined flight and ground test, and require significant data processing and analysis to establish findings, which are summarized from recent publications in this section. There is also still analysis in work with more future publications expected.

ECLIF3 (Airbus, DLR, Rolls-Royce, Neste, NRC Canada, University of Manchester)
The ECLIF3 ground-test and flight-test measurement campaigns took place in 2021 [1-4]. Emissions and contrail properties were measured from 100% Jet A-1 fossil fuel, 100% HEFA-SPK SAF, and a blend-fuel (blend fuel percentages specified in Table 1). For the flight tests, an Airbus A350-900 powered by Rolls-Royce Trent XWB-84 engines was followed by DLR's instrumented Dassault Falcon chase plane.

Comparing the 100% HEFA-SPK SAF to the fossil fuel baseline (which was itself a particularly clean-burning example of fossil fuel) yielded the following conclusions [**Error! Reference source not found.**1-4]:

- In-flight soot particle number emissions reduced by around 35%
- Contrail ice particle number reduced by around 56%
- The difference between reductions in soot particles and contrail ice particles is hypothesized to be due to the lower sulfur content of the HEFA-SPK SAF
- Simulations of the worldwide air traffic for the year 2018 activity using these results suggest approximately 26% reduction in global contrail radiative forcing from adoption of 100% SAF.
- There was no measurable effect on the emissions index (EI) of NO_x.
- The collected data will help development of ground to cruise correlations for particles and NO_x.
- Reduction in nvPM is greater at lower cruise power settings (~41% reduction) than at high cruise power settings (~22% reduction)
- The size distribution of nvPM is shifted towards smaller particles

- Reasonable correlation was found between measured nvPM levels and certain engine particle emission models [2,3,7] when adjusting to observations.
- In addition to contrail ice nucleation on soot, the fuel sulfur content can modulate the contrail ice crystal number. Medium and high sulfur fuels can increase and low sulfur fuels can decrease contrail ice crystal numbers.[4]

A further paper, containing analysis of particle emissions measurements taken during ECLIF3 ground tests, is currently in the review process at time of writing (Williams et al, in review).

VOLCAN (Airbus, Safran, Dassault Aviation, ONERA, DLR)
The VOLCAN (VOL avec Carburants Alternatifs Nouveaux) ground and flight-test measurement campaigns took place from 2021 to 2023. On-ground and in-flight emissions, as well as contrail properties were measured using Airbus A319neo and A321neo test aircraft powered by CFM LEAP-1A engines, burning 100% fossil Jet A-1, 100% HEFA-SPK SAF and blends of HEFA-SPK SAF with fossil fuel aromatics.

A specificity of VOLCAN compared to earlier campaigns is that the tested CFM LEAP-1A engine has a staged combustion chamber featuring lean burn low particle emissions technology [5]. To single out its impact, the campaign performed testing with this capability on but also deactivated by engine software change, called "forced rich burn." The campaigns yielded the following conclusions [5], and further work and analysis are ongoing:

- Lean burn reduces nvPM cruise emissions by approximately 3 orders of magnitude in flight, with all tested fuels, compared to forced rich burn and other campaigns with RQL combustors (as expected from the emission indices published in the ICAO engine emissions databank).
- The nvPM reduction trend with SAF seen in ECLIF is confirmed in forced rich burn combustion mode.
- In flight, total particulate matters (tPM), consisting of nvPM as well as volatile particles (vPM), were measured at a similar level as with forced rich burn.
- The composition of the vPM is constrained by observations and theory [5] and still uncertain: For Jet A-1, it is likely linked to sulfate aerosols, although other residual volatile species such as lubrication oil and organics may also play a role. For HEFA-SPK SAF, the vPM composition could consist of all of them except sulfuric acid.
- Similar levels of contrail ice particle number were measured in lean burn (soot poor) and rich burn (soot rich) mode.
- Precursors for contrail ice formation in soot poor conditions are not yet directly identified highlighting significant uncertainties: potential candidates are volatile species such as sulfuric acid, nitric acid, engine lubrication oil or other organics.

The fact that "substantial aircraft contrail formation" is also measured at low soot emission levels, is in line with the contrail formation theory [6,7,8]. But the role of specific species of vPM on contrail ice nucleation and its temperature dependency needs to be further investigated. Future campaigns are needed to understand the related processes, as well as the effects of engine variability, engine degradation and oil consumption and engine architecture. Future measurement campaigns are also needed to better characterize the shape, size distribution and optical properties of ice crystals from lean burn engines, as well as measurements to better understand the evolution of both soot-poor and soot-rich contrail properties with time. A further paper containing analysis of VOLCAN emissions results, including aerosols, is currently in the review process (Dischl et al, 2026).

The project was funded by French DGAC (French Civil Aviation Authority).

ecoDemonstrator (Boeing, NASA, Aerodyne, Missouri University of Science &Technology, University of Dayton, DLR, GE, Rolls-Royce, United, Alaskan Airlines, NRC Canada, Sandia National Laboratory, FAA)

Boeing ecoDemonstrator ground and flight measurement campaigns were completed during 2021, 2022, and 2023 with the overall objective to evaluate the emissions characteristics and contrail ice properties of burning different jet fuels in low soot emission engines and with extremely low sulfur fuel content.

The research began with 2021 ground tests that measured emissions from burning 100% HEFA-SPK SAF, SAF blends and Jet A-1 on a Boeing 737-9 aircraft. In 2022, additional ground emissions measurements were made on a Boeing 777-200ER ecoDemonstrator and a Boeing 787-10, comparing 100% HEFA-SPK SAF, SAF blends, low sulfur Jet A and Jet A-1. In 2023, flight tests used a Boeing 737-10 destined for United Airlines with CFM LEAP-1B engines as the test vehicle and NASA's instrumented DC-8 as a chase plane to measure emissions and contrail ice particles from 100% HEFA-SPK SAF, low sulfur Jet A and Jet A-1; these data were supplemented by ground-based measurements. During those flights the engines were operated in standard lean burn mode and in rich burn mode induced by a set of acceleration-deceleration maneuvers. In addition, various in-situ water-vapor sensors were flown to support sensor development and intercomparisons.

In order to get the most credible insights on the role of sulfur with engine emissions, considerable measures were taken to minimize residual fuel mixing in transport and handling to ensure accurate and consistent fuel properties during testing.

The ecoDemonstrator research campaigns have yielded the following preliminary conclusions, with further analysis and publication still expected:

- Use of HEFA-SPK SAF and low sulfur Jet A resulted in a decrease in total particulate matter (tPM) compared to Jet A-1.
- The highest tPM and nvPM per fuel burned were measured at low power settings (idle-60%) for all fuel types. A significant reduction in nvPM was measured at higher power settings (above 60%) when the CFM LEAP-1B engine was operated in lean burn conditions [9].
- Contrail ice particle numbers were lower for both the low sulfur Jet A and HEFA-SPK SAF for this CFM LEAP-1B engine compared to contrail ice particle numbers from the higher sulfur Jet A-1 fuel [10,11].
- Ice particle numbers were higher than expected considering ice nucleation driven by nvPM number only.
- Particles containing lubrication oil were measured by the aerosol mass spectrometer (AMS) in ground tests. This oil presumably originates from the oil vent into the exhaust core of the CFM LEAP-1B engine. This suggests that lubrication oil may play a role in the total particle mass

emissions from engines, particularly for low soot emission combustors when very low sulfur fuel is used.

- In a soot poor regime produced by the CFM LEAP-1B engine in lean burn, contrail ice formation is limited by the total number of particles emitted and forming in the plume. The total number of particles measured in this condition is most likely influenced by vented engine lubrication oil, sulfuric acid from fuel sulfur and other volatile organic emissions which may become contrail ice nuclei [11,12, 5].
- Similar to findings with HEFA-SPK SAF, when using low sulfur Jet A in lean burn, soot particle reduction is significantly greater than reduction in ice particle concentrations in the contrail.
- Preliminary data from the High Altitude Lidar Observation and High Spectral Resolution Lidar airborne instruments developed by NASA, which provides vertical profiles of cloud optical properties and atmospheric water vapor, showed the contrails from the Boeing 737-10 formed from Jet A-1 fuel had increased cloud optical thickness relative to those formed when burning the low sulfur Jet A and HEFA-SPK SAF.
- In-situ atmospheric measurements were made on the lead and trailing aircraft, as well as from the GOES satellite using the mesoscale mode (1-minute intervals in higher horizontal resolution). Useful case studies of the atmospheric role in contrail impact were therefore created, helping to inform requirements for sensor technology advancement necessary to improve forecast models [13].

Finding a Tailwind: Atmospheric Sensing and Measurement

Atmospheric forecasting, sensing and measurement technologies were critical to the operation of these flight tests, allowing scientists to predict and verify the areas where contrails will form and direct the test and chase aircraft accordingly. Improvements in the accuracy of these technologies, measurement range and operational capability is also necessary to better understand contrail formation, persistence and impact. Given that the improvement of these technologies is a part of the critical path towards mitigating the climate impact of contrails, this section highlights several efforts advancing atmospheric sensing and measurement as well as data availability.

The **In-service Aircraft for a Global Observing System (IAGOS)** is a long lasting public European Research Infrastructure for global observations of atmospheric composition from commercial aircraft, initiated in 2004 and established in 2014 as an international not for profit Association (IAGOS-AISBL). Its mission is to provide high quality data throughout the troposphere and lower stratosphere, and scientific expertise to understand the evolution of atmospheric composition, air quality, and climate.

IAGOS combines the expertise of scientific institutions with the infrastructure of civil aviation, including associated airlines and Airbus providing OEM support, in order to measure essential data of interest for weather prediction, climate change and air quality at a global scale. As of 2026, 10 commercial long-haul Airbus aircraft operating commercial flights are equipped with sensors measuring the concentration of various chemical species (ozone, CO, and pending the optional packages CO_2, NO_x/NO_y, CH_4 or aerosols) as well as humidity and cloud particles. The latter data continues to be important to progress contrails science, as demonstrated by recent advancements in prediction [14] and formation within clouds [15].

The **Aircraft Meteorological Data Relay (AMDAR)** program is a global initiative led by the World Meteorological Organization to provide real-time atmospheric data for improved weather forecasting. Within the AMDAR program, the FLYHT Water Vapor Sensing System (WVSS-II) is deployed on 140-150 aircraft globally, mainly operating in North America and Germany, to strategically improve humidity weather data for real-time assimilation to improve numerical weather prediction.

Due to limitations in the accuracy at upper tropospheric altitudes and operational requirements of current generation of atmospheric sensors, there are several emerging research programs to advance sensor technology and improve on the existing humidity datasets, enabling better prediction of contrail forming regions.

The United States Department of Energy Advanced Research Projects Agency 2023 funded program, **Predictive Real-time Emissions Technologies Reducing Aircraft Induced Lines in the Sky (PRE-TRAILS)** to invest in the technology and development of systems to predict aviation contrails capable of informing pilots and ground controllers in real-time whether an airplane is likely to produce contrails or contrail cirrus. The program focused on three technological areas: (1) aircraft, environmental data and sensor development, including water vapor sensing technologies; (2) improved predictive models through integration of in-situ sensed weather data; and (3) observer data resources to develop an integrated and more accurate aviation contrail predictive system. ARPA-E funded four projects to pursue this effort led by RTX/Collins Aerospace, General Electric, Northrup Grumman, and Universities Space Research Association. These programs have advanced learning on emerging atmospheric sensing technology capabilities and limitations.

Light Detection and Ranging (lidar) technology is an established and effective tool for atmospheric measurement that can be applied to contrail prediction and observation. In November 2024, GE Aerospace, NASA and DLR partnered on a series of unique flight tests using lidar to help further the aviation industry's understanding of contrails, **Flights for the Contrail Optical Depth Experiment (CODEX).** NASA Langley Research Center's G-III aircraft followed GE Aerospace's Boeing 747 Flying Test Bed in the sky and scanned the aircraft wake with lidar technology to generate three-dimensional imaging of contrails and their optical properties to better characterize how contrails form and how they behave over time.

These developing atmospheric sensing capabilities have potential to continue building existing atmospheric composition datasets by offering more accurate and broad spread measurements of humidity as well as contrail observations for the purpose of improving weather modeling and validating contrail formation models which are two key priorities for understanding contrail formation, persistence and impact.

The View from the Upper Troposphere

The ECLIF3, VOLCAN and ecoDemonstrator flight and ground campaigns have substantially expanded our understanding of how fuel type and engine technology influence non-CO_2 emissions and contrail formation. These programs and other efforts have also expanded our understanding of the influence of atmospheric conditions. Advancing this knowledge is critical to enabling the two fundamental pathways to mitigate the climate impact of contrails: reducing contrail formation through changes to fuels and engine technologies and operational contrail avoidance (adjusting flight paths to avoid contrail-forming regions).

The key findings show increasing alignment, knowledge and expertise over time. This is thanks to the involvement of experts from airlines, national aerospace agencies, certification authorities, airspace navigation service providers, national research laboratories and many academic institutions who worked across programs and brought the latest analysis and best practices to each program. The partnership of these stakeholders has ensured that there is significant progress from program to program as well as a growing collection of robust scientific analysis and publication to build on.

With respect to the impact of fuel type, these campaigns demonstrated potential to reduce contrail formation and persistence based on varying fuel properties. Significant work on sustainable aviation fuels in recent years has focused on reducing lifecycle carbon emissions. The findings across these research campaigns suggest that contrails formation can be reduced by reducing fuel aromatic and sulfur content and that HEFA-based sustainable aviation fuels can have characteristics favorable to both carbon emissions and contrails reduction.

The research campaigns also demonstrated that engine technology has an impact on emissions properties and contrail formation and persistence. The campaigns found that across all tested fuel types, lean burn combustion drives a significant reduction in soot particle number. VOLCAN and ecoDemonstrator analysis focused on ice particle measurement in the lean burn combustion soot poor regime also showed that contrail formation can occur even in the near-absence of soot. This indicated that volatile species such as sulfate aerosols, lubrication oil, or organic compounds could play a role in contrail formation [5, 11,12,10]. Further, the 2023 ecoDemonstrator program tested low sulfur fuels and found there was still significant contrail formation in the soot poor regime. This suggests that even when both soot and sulfate aerosols are minimized, lubrication oil and organics remain as candidates for ice nuclei [5].

These findings indicate that engine technology advancements prioritizing reduction of soot emissions are important to reducing contrail formation. However, further studies need to be conducted to understand the role of lubrication oil and its influence on contrail ice and particle counts. The location of the lubrication oil vapor vent may influence how and to what extent emitted semi-volatile oil vapors contribute to volatile particulate matter emitted and to subsequent contrail ice particle nucleation [5, 16,17,18].

Findings from the research will also inform future water vapor sensor development critical to enabling operational contrail avoidance, a key strategy to address the climate impact of contrails. More precise atmospheric data will enable improved weather models and prediction success.

The following table summarizes the key findings by program and shows the progression across programs. All tests included controlled engine operations to achieve desired exhaust regimes as well as testing with JetA-1 and 100% HEFA-SPK SAF.

Table 1 - Research Campaign Summary

Campaign	Aircraft	Engine*	Fuels Tested*	Key Findings
ECLIF3 2021	A350-900	Trent XWB-84	• 62% Jet A-1 +38% HEFA-SPK SAF	Using 100% HEFA-SPK SAF on an A350/Trent XWB reduced soot nvPM by ~35% and contrail ice particle numbers by ~56% relative to a clean Jet A-1 baseline. In addition to contrail ice nucleation on emitted soot particles, the fuel sulfur content may play a role in modulating contrail ice nucleation. The greatest percentage reduction in soot was observed at low engine power settings reinforcing results from prior campaigns.
VOLCAN 2021 2022 2023	A319neo A319neo A321neo	LEAP-1A	• HEFA-SPK SAF + low aromatics • HEFA-SPK SAF + high aromatics • 36% Jet A-1 +64% HEFA-SPK SAF	Findings of soot and contrail ice particle concentration reductions due to fuel type reinforced ECLIF3 findings in soot rich regimes. Three orders of magnitude reduction of nvPM at cruise were measured with the LEAP-1A in lean burn compared to rich burn combustion. Ice particles and total particulate matter had similar concentrations in lean burn and rich burn combustion. This indicates that soot is not the dominant driver of contrail formation in the soot-poor regime and other species such as sulfate aerosols, lubrication oil, or organic compounds play a key role.

ecoDemonstrator 2021 2022 2023	B737-9 B777-200ER B787-10 B737-10	LEAP-1B GEnx-1B Trent-892	• 70% Jet A-1 +30%– HEFA-SPK SAF Blend • 50% Jet A-1 +50% – HEFA-SPK SAF Blend • Low sulfur Jet A	Findings of reduced soot and similar contrail ice particle number for fuels and engine operating conditions are consistent with VOLCAN findings in soot poor and soot rich regimes. Similar to findings with HEFA-SPK SAF, when using low sulfur Jet A-1 in lean combustion, soot particle reduction is significantly greater than reduction in contrail ice particles which suggests that even when soot and sulfate aerosols are minimized, residual volatile species could act as condensation nuclei for contrail formation. Oil-coated soot particles originating from lubrication oil vented into the core flow by the CFM LEAP-1B engine were sampled by the aerosol mass spectrometer (AMS). Several water vapor instruments flying on both the B737-10 and DC-8 were intercompared with the "gold standard" NASA Diode Laser hydrometer (DLH).

**All tests included controlled engine operations to achieve desired exhaust regimes* as well as testing with *JetA-1 and 100% HEFA-SPK SAF*

Charting a Path Forward for Future Research

Future ground and flight tests using experimental design and methodology influenced by the results of ECLIF3, VOLCAN and ecoDemonstrator will continue to accelerate the development of contrails science. Better understanding contrail formation, persistence and impact as well as emissions properties is critical to enabling mitigation of aviation's climate impacts through advanced engine and fuels technology and operational contrail avoidance.

Future research campaigns should build on this work to study particulate matter and ice particle formation across engine design and cruise power settings, fuel composition and oil venting conditions. A special focus could be understanding the particle number size distribution in a total particle-based scheme. Increasing in-flight and remote sensing data to obtain improved temperature, humidity and contrail lifetime data along with the emissions data would also increase the opportunity for future research to progress contrail evolution and persistence models.

To achieve these high-level objectives, a pathway to guide the next generation of research is proposed:

Evolve objectives with learning:

1. Shape research around the understanding of impacts to particle number size distribution for both nvPM and vPM and their connection to contrail formation.

2. Include model development and validation (meteorological modeling, contrail microphysics, global radiative forcing, nvPM or tPM to ice conversion parameterizations) in research objectives to collect data for model initialization, evaluation and improvement.

Improve methods and capability:

1. Standardize test methodologies and reporting protocols to facilitate integrated reporting and data exchange.
2. Develop chase plane platforms capable of sampling at cruise conditions in the optimal positions for plume sampling.
3. Advance chase plane instrumentation with respect to measured aerosol parameters and improve measurement methodology in both contrail forming and non-contrail forming conditions at different separations behind the test aircraft.

Test on ground and in-flight:

1. Measure nvPM and vPM at cruise power settings (i.e., precursor gases, volatile and non-volatile particles, aerosol size and composition, properties of ice nucleating particles) when forming and not forming contrails.
2. Include controlled manipulations of fuel sulfur and aromatic composition and content plus rigorous fuel handling.
3. Quantify engine lubrication oil venting from different engines across power settings.
4. Measure microphysical and optical properties of young and persistent contrails with in-situ instruments and lidar, including satellite studies.
5. Investigate the vapor deposition and scavenging on existing plume particles with modeling studies [5]
6. Increase number of measurements and accuracy of ambient temperature and relative humidity data and use of remote sensing such as high-resolution geostationary imagery and High Spectral Resolution Lidar (HSRL) to capture the role of the atmospheric conditions and contrail lifetime.
7. Include satellite information in contrail analysis.

Aside from the research, the collaboration model for these large-scale research campaigns is unique. Multi-stakeholder governance (airframers, engine OEMs, research labs and regulators) is helpful in ensuring robust and effective test matrices, access to shared scientific datasets, and publication of findings.

Open Skies

The industry-led initiatives in this short overview are a subset of the science efforts being conducted on the topic globally including significant efforts in academic, government and non-profit research organizations. These organizations play an integrating role across projects and lead on synthesizing results and analysis into publications, increasing the momentum of advancement and creating vital links across industry. As called out in the July 2024 industry Chief Technology Officers joint statement, this type of collaboration and co-investment has significant benefits for customers, consumers, and the public and must continue.

For more information about upcoming projects and research that continue to advance the science of emissions properties and contrails formation, persistence and impact, refer to Appendix A.

For more information about the state of science and recommended research enabling contrail impact mitigation the following resources are recommended:

- European Union Aviation Safety Agency (Aviation Non-CO2 Expert Network) - Gaps and Uncertainties on Aviation Non-CO2 Effects on Climate (2026)
- The National Academy of Sciences, Engineering and Medicine - Research Agenda for Reducing the Climate Impact of Aviation Induced Cloudiness and Persistent Contrails from Commercial Aviation (2025)
- United States Federal Aviation Administration, National Aeronautics and Space Administration, and National Oceanic and Atmospheric Administration - Contrails Research Roadmap - Version 1.0 (2025)
- International Civil Aviation Organization (Committee on Aviation Environmental Protection, Impacts and Science Group) - Committee on Aviation Environmental Protection Impacts and Science Group Contrail Science Workshop Report (2025)
- International Air Transport Association - Aviation Contrails and Their Climate Effect: Tackling Uncertainties and Enabling Solutions (2024)

APPENDIX A

On the radar...Ongoing & Upcoming Research

Similar to the past five years, efforts across the industry continue to increase in quantity and level of collaboration. The key learnings from ECLIF3, VOLCAN, ecoDemonstrator and the work on atmospheric sensing have shaped a next generation of funded projects focused on improving the science and understanding of contrail formation, persistence, impact and mitigation. The following section highlights recently publicized projects with corresponding scope and partners.

QRITOS (Rolls-Royce, British Airways, Heathrow Airport, Imperial College London, Air bp)
QRITOS (Quantifying Reduction In Thermal contrails by Optimising SAF) is a two-year project that started in May 2025. Its goal is to explore how the value proposition of SAF might be enhanced through smart usage by potentially increasing the contrail mitigation potential of a given amount of SAF while retaining the SAF life-cycle CO_2 reduction relative to fossil fuel.

The project is motivated by the understanding that the majority of contrail climate impact is attributable to a small proportion of flights and builds upon results from recent programs such as ECLIF2 and ECLIF3 which compared the properties of contrails produced when burning fossil fuel versus burning SAF in blend ratios up 50% (ECLIF2) and 100% (ECLIF3).

Working within an operational environment at one of the world's busiest airports, QRITOS aims to demonstrate the logistical feasibility of deploying SAF in a targeted fashion so that it is supplied at a relatively high blend ratio (~ 50%) to a small number of flights which are forecasted to form strongly warming contrails, rather than being supplied at a relatively low blend ratio to all flights irrespective of their contrail outcomes.

QRITOS also aims to demonstrate the use of advanced satellite image analysis methods to detect and characterize contrails formed during 2026 flight testing using SAF as well as during comparison flights using Jet A fuel.

QRITOS is co-funded by the Non-CO_2 Program of the UK's Aerospace Technology Institute (ATI). [24,25,26]

TRACE (Airbus, Imperial College)
The TRACE (Targeting Reduced Aircraft Contrail Emissions) project aims to deploy several approaches to addressing the effects of contrails. It includes developing critical contrail modelling and analysis capabilities, together with sensor technology to better permit operational contrail avoidance. The project aligns with the Fuel Characteristics, Aircraft Systems and Knowledge, Data and Ops streams in the ATI Non-CO_2 Technology Roadmap.

TRACE is co-funded by the Non-CO_2 Program of the UK's Aerospace Technology Institute (ATI). [27]

MIST (Honeywell, Boeing, U. Reading)
MIST (Mitigating Impact of Sustained Contrails) will develop an aircraft-based prototype water vapor sensor designed to improve the understanding and mitigation of climate impacts from aircraft creating

persistent contrails. This research and development project, will not only focus on advancing sensor technologies, but also the modeling capabilities to increase the forecast accuracy of ISSRs.

MIST is co-funded by the Non-CO_2 Program of the UK's Aerospace Technology Institute (ATI).

CICONIA MET

CICONIA MET (2026-2029) will develop meteorological and climate services for airlines, air navigation service providers and network managers to improve flight safety and efficiency, enhancing mitigation of adverse weather conditions such as convection, icing and turbulence, while reducing aviation's environmental impact. The services support flight trajectory optimization considering weather and climate effects.

The project leverages existing and next-generation aircraft sensors and datalink infrastructure, feeding weather and climate forecast models. Sensor data, enriched with alternative ground measurements, are processed and shared with end users. CICONIA MET will design the service and data architecture, define interfaces, support standardization, and validate results through lab exercises and flight tests.

Building on prior SESAR projects such as CICONIA, the consortium includes original equipment manufacturers, avionics and communications suppliers, weather services, research organizations, airlines and air navigation service providers, supported by a stakeholder outreach body to disseminate results.

CICONIA MET is co-funded by the European Union SESAR Joint Undertaking within the framework of its Digital European Sky Industrial Research program.

ECLIF-X (AIRBUS, DLR, P&W)

ECLIF-X (Emissions and Climate Impact of Alternative Fuels) is an important research and development project reflecting industry's commitment to reducing aviation's climate impact.

The flight test campaign occurred in November 2025 and is a continuation of previous related campaigns (ECLIF1-3), where the emissions and contrails of other engine types fitted with the rich-burn combustor technology were measured with different fuels, including 100% sustainable aviation fuel (SAF).

ECLIF-X aims to assess the effect of low-sulfur/low-aromatics fuel on the PW1100G-JM engine's emissions and contrail properties by measuring emissions on an A321XLR test aircraft flying with three different fuels. During the flight test campaign, in-flight emission and contrail measurements are conducted by scientists from the German Aerospace Center (DLR) using a fully instrumented Falcon 20E research aircraft. Drawing on more than 30 years of expertise, the DLR team tracks the A321XLR at distances of 50 to 300 meters to collect precise emissions data.

The 'X' in ECLIF-X refers to engine manufacturer Pratt & Whitney's TALON-X rich-burn combustor, which is designed to reduce gas turbine's soot emissions. These emissions include the small particles that impact the formation of contrail ice crystals. The A321XLR's Pratt PW1100G-JM engine is equipped with the combustor, and the powerplant's emissions are the focus of the campaign. [28]

Analysis of test data is on-going. This new dataset will help improve emission and contrail modelling and inform work on future fuel standards and design choices.

OXFUEL (Oxccu with the support of Estuaire & Safran)
OXCCU has developed a novel Power-to-Liquids technology that converts CO_2 and green hydrogen into OXFUEL, a synthetic crude oil with an exceptionally high yield of sustainable aviation fuel. The project evaluates three hydrotreatment upgrading routes to convert OXFUEL into SAF blending components with distinct aromatic contents: conventional (8-24%), low (~3%), and zero-aromatic fuels. These routes span the full practical range of SAF deployment scenarios: a zero-aromatic fuel representing a fully drop-in compatible SAF, a low-aromatic blend representing a middle ground that could still meet OEM requirements for existing aircraft, and a conventional aromatic blend aligned with current ASTM specifications.

The core objective is to quantify how fuel aromatic content influences non-CO_2 climate effects, including particulate emissions, contrail formation, and radiative forcing. Each fuel variant will undergo full property characterization and particulate emissions testing at accredited laboratories. The resulting combustion data will provide a robust empirical basis to inform non-CO_2 modelling.

This dataset will be used by Estuaire, leveraging their validated global aviation non-CO_2 emissions framework, to generate comparative, model-backed projections of real-world climate performance across the three fuel types at global fleet scale. A techno-economic-environmental assessment will then identify the optimal upgrading pathway based on cost, efficiency, and total climate benefit.

The project will deliver evidence to inform SAF specifications, certification pathways, and procurement strategies for OEMs, airlines, and regulators. This research is positioned to contribute meaningfully to the development of next-generation SAF standards and the evidence base for non-CO_2 policy frameworks within ASTM and ICAO processes.

OXFUEL is co-funded by the non-CO_2 program of the UK's Aerospace Technology Institute (ATI).

PACIFIC (Airbus, Rolls-Royce, NESTE, Johannes Gutenberg University Mainz, University of Helsinki, The Manchester Metropolitan University, The University of Sheffield, DLR-The German Aerospace Center, Erdyn consulting, Cyprus Institute, Cardiff University)
The PACIFIC project, funded by the European Union, started in January 2025 and will last until June 2028.

PACIFIC (Particle emissions, Air Quality and Climate Impact related to Fuel Composition and Engine Cycle) seeks to bridge the gap in understanding aviation's non-CO2 emissions by testing an unprecedented range of fuels under controlled conditions. The project will ensure consistency in combustion parameters and hardware similarity from lab-scale experiments at the German Aerospace Center (DLR) to full aircraft engine tests at Airbus Toulouse.

The research will focus on understanding how soot forms during fuel combustion, using improved prediction tools to better anticipate its presence in engine emissions based on the detailed fuel composition. It will also analyze the quantity of fine particles released at different engine power levels, refining methods to estimate their impact from ground tests to real flight conditions. Another key aspect is assessing how these particles contribute to contrail ice crystal formation using advanced measurement techniques. Finally, the project will evaluate the broader climate effects of these emissions by examining how different fuel compositions and engine settings influence contrail formation and properties, and their impact on global warming.

By consolidating these insights, PACIFIC will contribute to a robust cost-benefit assessment of various fuel options, providing crucial inputs for potential future fuel-related regulations. The project will ultimately help define new fuel specifications aimed at reducing aviation’s climate and air quality impact.

APPENDIX B

ECLIF2 / ND-MAX (DLR, NASA, NRC Canada, Aerodyne Research, Missouri S&T)
ECLIF2 / ND-MAX (NASA/DLR Multidisciplinary Airborne eXperiment / Emission and CLimate Impact of alternative Fuel 2) ground and flight measurement campaigns were carried out in 2018, using DLR's A320 aircraft with IAE V2527-A5 engines as the test vehicle. In-flight measurements were taken by NASA's instrumented DC-8 aircraft operating as a chase-plane. Emissions from 5 different fuels (2 fossil reference kerosenes and 3 blends comprising up to 50% HEFA-SPK SAF) were measured.

Flight test results [19,21,22] and conclusions included the following (quoted from the references) :

- "Burning low aromatic sustainable aviation fuel can result in a 50 to 70% reduction in soot and ice number concentrations and an increase in ice crystal size."
- "Meaningful reductions in aviation's climate impact could therefore be obtained from the widespread adoption of low aromatic fuels."
- "Results imply that bi-cyclic naphthalenes are more efficient soot precursors than mono-cyclic aromatic or aliphatic hydrocarbon structures."

Ground test results [23] included the following:

- Reductions of up to 70% in particle mass emissions were observed at low power settings relative to a fossil fuel.
- Emitted particle numbers were significantly impacted by changes in the naphthalene content of the fuel.
- Comparisons of a SAF with a fossil fuel of similar fuel hydrogen content showed similar soot tendencies.
- No significant difference in NO_x emissions index was observed between the various fuels.
- "The particle mitigation potential of SAF blends tend to decrease with increasing power settings of the engine."

REFERENCES

ECLIF3

1. Märkl, R. S., Voigt, C., Sauer, D., Dischl, R. K., Kaufmann, S., Harlaß, T., Hahn, V., Roiger, A., Weiß-Rehm, C., Burkhardt, U., Schumann, U., Marsing, A., Scheibe, M., Dörnbrack, A., Renard, C., Gauthier, M., Swann, P., Madden, P., Luff, D., Sallinen, R., Schripp, T., and Le Clercq, P.: (2024). Powering aircraft with 100% sustainable aviation fuel reduces ice crystals in contrails. Atmospheric Chemistry and Physics, 24(7), 3813–3837. https://doi.org/10.5194/acp-24-3813-2024

2. Harlass, T., Dischl, R., Kaufmann, S., Märkl, R., Sauer, D., Scheibe, M., Stock, P., Bräuer, T., Dörnbrack, A., Roiger, A., Schlager, H., Schumann, U., Pühl, M., Schripp, T., Grein, T., Bondorf, L., Renard, C., Gauthier, M., Johnson, M., Luff, D., Madden, P., Swann, P., Ahrens, D., Sallinen, R., and Voigt, C. (2024). Measurement report: In-flight and ground-based measurements of nitrogen oxide emissions from latest-generation jet engines and 100% sustainable aviation fuel. Atmospheric Chemistry and Physics, 24(20), 11807–11822. https://doi.org/10.5194/acp-24-11807-2024

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

4. Dischl, R., Märkl, R., Sauer, D., Voigt, C., Harlaß, T., Scheibe, M., Hahn, V., Kaufmann, S., Marsing, A., Dörnbrack, A., Roiger, A., Yu, F., Gauthier, M., Renard, C., Swann, P., Johnson, M., Ahrens, D., Sallinen, R., Eckel, G., & Le Clercq, P. (2025). Fuel sulfur content can modulate contrail ice crystal numbers. Communications Earth & Environment, 6, Article 902. https://doi.org/10.1038/s43247-025-02951-5

VOLCAN

5. Voigt, C., Märkl, R., Sauer, D., Dischl, R., Renard, C., Seeliger, K., Yu, F., Kaufmann, S., Bräuer, T., Jurkat-Witschas, T., Le Chenadec, G., Moreau, J., Requena-Esteban, E., Bonne, N., Vals, M., Roche, A., Zelina, J., Dörnbrack, A., Eirenschmalz, L., Heckl, C., Horst, E., Lichtenstern, M., Marsing, A., Neumann, G., Roiger, A., Scheibe, M., Stock, P., Giez, A., Eckel, G., & Le Clercq, P. (2026). Substantial aircraft contrail formation at low soot emission levels. Nature, 652, 112–118. https://doi.org/10.1038/s41586-026-10286-0

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

7. Teoh, R., Schumann, U., Gryspeerdt, E., Shapiro, M., Molloy, J., Koudis, G., Voigt, C., & Stettler, M. E. J. (2022). Aviation contrail climate effects in the North Atlantic from 2016 to 2021. Atmospheric Chemistry and Physics, 22(16), 10919–10935. https://doi.org/10.5194/acp-22-10919-2022

8. Yu, F., Kärcher, B., & Anderson, B. E. (2024). Revisiting contrail ice formation: Impact of primary soot particle sizes and contribution of volatile particles. Environmental Science & Technology, 58(40), 17650–17660. https://doi.org/10.1021/acs.est.4c04340

ecoDemonstrator

9. Moore, R. H., et al. (2025, March). [Presentation]. RAeS/IATA Contrails Conference.
10. Brauer, T., et al. (2024). Contrail measurements in the low-soot regime: Boeing ecoDemonstrator Explorer experiment [Poster A51M-1856]. AGU Fall Meeting.
11. Miller, R., et al. (2025). Preliminary data analysis of the 2023 Boeing ecoDemonstrator Explorer SAF emissions and contrail project [Conference presentation]. AGU Fall Meeting.
12. Baughcum, S. L., et al. (2024). Overview of the 2023 Boeing ecoDemonstrator Explorer SAF emissions and contrail project [Conference presentation]. AGU Fall Meeting.
13. Rahmes, T., Hoffman, J. P., Wimmers, A. J., Diskin, G., Gatebe, C., Miller, R., DiGangi, J. P., et al. (2025). Meteorological observations from aircraft and satellites for contrail cirrus evolution observed in flight testing. In 105th Annual AMS Meeting 2025 (Vol. 105, p. 450939).

IAGOS - related or enabled

More than 500 scientific articles have been published related to or enabled by the IAGOS project and data, the full list can be found at: https://www.iagos.org/scientific-publications/. Among the latest ones related to contrails science are:

14. Wolf, K., Bellouin, N., Boucher, O., Rohs, S., & Li, Y. (2025). Correction of ERA5 temperature and relative humidity biases by bivariate quantile mapping for contrail formation analysis. Atmospheric Chemistry and Physics, 25(1), 157–181. https://doi.org/10.5194/acp-25-157-2025
15. Petzold, A., Khan, N. F., Li, Y., Spichtinger, P., Rohs, S., Crewell, S., Wahner, A., & Krämer, M. (2025). Most long-lived contrails form within cirrus clouds with uncertain climate impact. Nature communications, 16(1), 9695. https://doi.org/10.1038/s41467-025-65532-2

Other sources:

16. Moore, R.H., Anderson, B., DiGangi, J., Miech, J., Wiggins, E., Winstead, E., Dominguez-Medina, S., Klettlinger, J., Miake-Lye, R., Fortner, E., Pothier, M., Achterberg, S., Kehoe, L., Satterfield, W., Woelk, K., Whitefield, P., Barry, K., Perkins, R., Booth, P., Cook, B., House, P., Salamone, J., Ahrens, D., Bake, S., Didyk-Wells, N., Tighe, D. (2026). Sustainable aviation fuel effects on aircraft engine particle emissions measured during the 2024 Gulfstream ground test. https://doi.org/10.2514/6.2026-0848
17. Ponsonby, J., King, L., Murray, B. J., & Stettler, M. E. J. (2024). Jet aircraft lubrication oil droplets as contrail ice-forming particles. Atmospheric Chemistry and Physics, 24(3), 2045–2058. https://doi.org/10.5194/acp-24-2045-2024
18. Decker, Z. C. J., Alpert, P. A., Ammann, M., Anet, J. G., Bauer, M., Cui, T., Durdina, L., Edebeli, J., Gysel-Beer, M., Prévôt, A. S. H., Qi, L., Slowik, J. G., Spirig, C., Tinorua, S., Ungeheuer, F., Vogel, A., Zhang, J., & Brem, B. T. (2024). Emission and Formation of Aircraft Engine Oil Ultrafine Particles. ACS ES&T Air, 1(12), 1662–1672. https://doi.org/10.1021/acsestair.4c00184

ECLIF2/ND-MAX and ACCESS

19. Voigt, C., Kleine, J., Sauer, D., et al. (2021). Cleaner burning aviation fuels can reduce contrail cloudiness. Communications Earth & Environment, 2, 114. https://doi.org/10.1038/s43247-021-00174-y

20. Moore, R. H., Thornhill, K. L., Weinzierl, B., Sauer, D., D'Ascoli, E., Kim, J., Lichtenstern, M., Scheibe, M., Beaton, B., Beyersdorf, A. J., Barrick, J., Bulzan, D., Corr, C. A., Crosbie, E., Jurkat, T., Martin, R., Riddick, D., Shook, M., Slover, G., Voigt, C., … Anderson, B. E. (2017). Biofuel blending reduces particle emissions from aircraft engines at cruise conditions. Nature, 543(7645), 411–415. https://doi.org/10.1038/nature21420

21. Bräuer, T., Voigt, C., Sauer, D., Kaufmann, S., Hahn, V., Scheibe, M., Schlager, H., Huber, F., Le Clercq, P., Moore, R. H., & Anderson, B. E. (2021). Reduced ice number concentrations in contrails from low-aromatic biofuel blends. Atmospheric Chemistry and Physics, 21(22), 16817–16826. https://doi.org/10.5194/acp-21-16817-2021

22. Bräuer, T., Voigt, C., Sauer, D., Kaufmann, S., Hahn, V., Scheibe, M., et al. (2021). Airborne measurements of contrail ice properties—Dependence on temperature and humidity. Geophysical Research Letters, 48(8), e2020GL092166. https://doi.org/10.1029/2020GL092166

23. Schripp, T., Anderson, B. E., Bauder, U., Rauch, B., Corbin, J. C., Smallwood, G. J., Lobo, P., Crosbie, E. C., Shook, M. A., Miake-Lye, R. C., Yu, Z., Freedman, A., Whitefield, P. D., Robinson, C. E., Achterberg, S. L., Köhler, M., Oßwald, P., Grein, T., Sauer, D., Voigt, C., Schlager, H., LeClercq, P. (2022). Aircraft engine particulate matter emissions from sustainable aviation fuels: Results from ground-based measurements during the NASA/DLR campaign ECLIF2/ND-MAX. Fuel, 325, 124764. https://doi.org/10.1016/j.fuel.2022.124764

Related and upcoming project press releases & news articles

1. GE Aerospace. (2024, November 15). GE Aerospace and NASA partnering on flight tests to accelerate industry's understanding of contrails [Press release]. https://www.geaerospace.com/news/press-releases/ge-aerospace-and-nasa-partnering-flight-tests-accelerate-industrys-understanding
2. Rolls-Royce. (2025, November 4). Rolls-Royce leads UK project to demonstrate smarter use of sustainable aviation fuel [Press release]. https://www.rolls-royce.com/media/press-releases/2025/04-11-2025-rr-leads-uk-project-to-demonstrate-smarter-use-of-sustainable-aviation-fuel.aspx
3. Imperial College London. (2025, November 7). Imperial joins Rolls-Royce to target contrails with smarter SAF deployment [News article]. https://www.imperial.ac.uk/news/271433/imperial-joins-rolls-royce-target-contrails-with/
4. Flight Global. (2025, November 4). British Airways seeks "double-whammy win" from targeted SAF use to prevent contrail formation. https://www.flightglobal.com/british-airways/2025/11/british-airways-seeks-double-whammy-win-from-targeted-saf-use-to-prevent-contrail-formation/
5. Airbus. (2026, March). Chasing contrails: How Airbus-backed research is tackling non-CO2 emissions. https://www.airbus.com/en/newsroom/stories/2026-03-chasing-contrails-how-airbus-backed-research-is-tackling-non-co2-emissions

6. DLR. (n.d.). ECLIF-X project: Studying contrails [LinkedIn post]. LinkedIn. https://www.linkedin.com/posts/dlr_eclif-x-project-studying-contrails-activity-7400115149916831744-71k_/

Acknowledgements

Authors

Philippe Mattei, Airbus S.A.S
Corinne Marizy, Airbus S.A.S
Charles Renard, Airbus S.A.S
Steve Baughcum, Boeing
Ellen Ebner, Boeing
Rose Miller, Boeing
Tim Rahmes, Boeing
Joe Zelina, GE
Peter Swann, Rolls-Royce
Sean Bradshaw, RTX
Kevin Kronfeld, RTX
Valérie Guenon, Safran
Nicolas Jeuland, Safran