# Addressing Non-$CO_2$ Emissions – the way towards clean and competitive aviation

By Christiane Voigt (DLR), Anthony Brown (NRC), Greg Smallwood (NRC), Leonid Nichman (NRC), Sean Yun (NRC), Pervez Canteenwalla (NRC), and Philippe Novelli (ONERA), and Adél Schröpfer (DLR/IFAR)

The International Forum for Aviation Research (IFAR) is a global network that connects 26 active aviation research organizations from all inhabited continents, collectively employing over 40,000 researchers. As the only global network of its kind, IFAR fosters collaboration through its core activities, which include facilitating information exchange and networking among member organizations, discussing technical challenges to enable multilateral international collaborations, supporting human resource development for early-career researchers, and forming partnerships with external entities such as International Civil Aviation Organization (ICAO) and International Council of the Aeronautical Sciences (ICAS). IFAR maintains a strong partnership with ICAO. Together, we strive to advance innovation in aviation with a focus on sustainable development.

This scientific paper originates from IFAR's active participation in the ICAO Symposium on Non-$CO_2$ Emissions, held in Montreal in September 2024. Developed as part of IFAR's dedication to tackling the challenges of sustainable aviation, the paper synthesizes insights from presentations delivered by IFAR members, DLR (Deutsches Zentrum für Luft- und Raumfahrt), NRC (National Research Council Canada), and ONERA (Office National d'Etudes et de Recherches Aérospatiales) during the symposium. These insights focus on key research areas, including the physics underlying contrail, cloud, and emission formation and interactions, the evaluation of current and future aviation technologies' climate impact, and the exploration of mitigation strategies aimed at reducing the combined effects of $CO_2$ and non-$CO_2$ emissions.

## DLR Insight

Today, the effective radiative forcing from contrails is on par with that from aviation's $CO_2$ emissions since the historical start of air traffic. Also, global air traffic has recovered from the 2020 pandemic and is expected to triple by 2055. Hence, the international aviation strategy needs to combine aviation competitiveness and growth with a scenario that curbs aircraft emissions, and related climate effects. DLR and international IFAR partners investigate short, mid and long-term reduction measures by air traffic management, sustainable aviation fuels (SAF) and e-fuels, including hydrogen, as well as engine technology. In addition to $CO_2$, some of these measures have the potential to reduce aircraft non-$CO_2$ effects, e.g. particle emissions and contrails (see Figure 1).

The implementation of ATM measures to avoid contrails by climate optimized flight routing within the next decade could have fast positive effect on climate at low operational costs. In this context, DLR and partners develop models to predict regions with warming contrails on a single flight and a fleet bases and support airline demonstration trials to study the operational feasibility by ATM. Here, DLR advances science to assess the contrail climate benefits and related trade-offs with respect to operational costs. DLR also supports the development of the Monitoring, Reporting and Verification System for non-$CO_2$ effects by the European Parliament.

Before the release to the market, the engine's particle emissions are measured and monitored by ground tests for specific test points during the take-off and landing

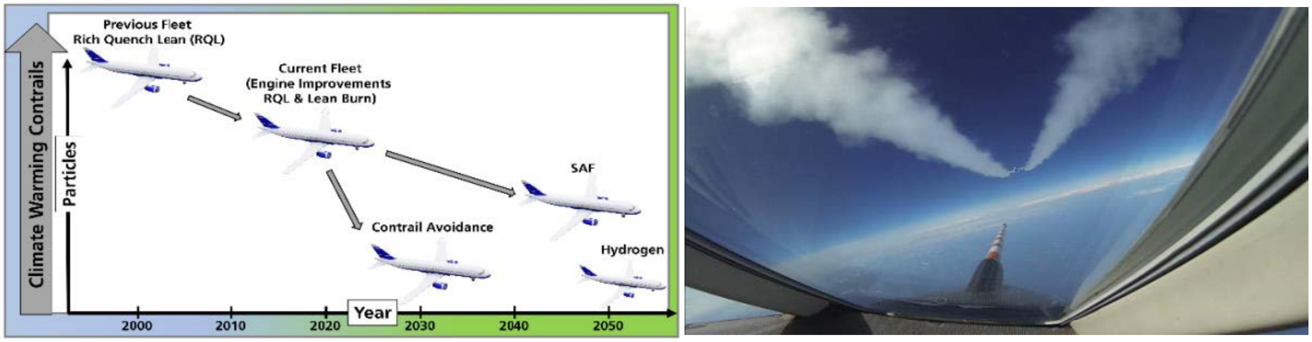


**FIGURE 1:** Left: Timescales of aviation particle reduction measures through ATM, low aromatic fuels and engine technology. Right: DLR research aircraft Falcon probing the contrails from an Airbus aircraft fueled with 100 % SAF (Märkl et al., ACP, 2024; Dischl et al., ACP, 2024; Harlass et al., ACP, 2024) (right).

cycle. While the extrapolation of aircraft $CO_2$ emissions to cruise flight altitudes is straightforward, there is the need to measure the engine's particle emissions at cruise altitudes in order to quantify non-volatile and volatile particle concentrations emitted at cruise and to calculate related climate effects. Over the last four decades, DLR, together with partners from industry, has built up a unique expertise for chase flights for research. With its instrumented research aircraft Falcon, DLR can probe the emissions and contrails in 50 m to 100 km distance to the preceding aircraft. The acquired data sets quantify engine trace gas and particle emissions at cruise help to constrain models and measure the particle and contrail reduction impact by SAF and e-fuels. DLR has worked with NRC, Airbus and Rolls-Royce on particle reduction by 100% sustainable aviation fuels within the ECLIF3 project[1] (see Figure2).

## NRC Insight

Canada has the second largest airspace in the world and because non-$CO_2$ emissions can have magnified wide-area, regional and local effects on the climate, there is a rationale and an opportunity for Canada to make significant contributions to this field of study. With a robust foundation in atmospheric modeling and meteorology, Canada aims to leverage its expertise to contribute meaningfully to international efforts in understanding and mitigating these emissions. The NRC has been at the forefront of research efforts in measuring emissions from aircraft using Jet A1 and SAF, commencing in 2011. Also, since 2011, NRC has supported major emissions ground test campaigns, leading innovations in measuring black carbon[2], and developing new technical standards and regulations. Through its High-Altitude Atmospheric Research Aircraft, the NRC has conducted comprehensive in-flight emissions and contrail studies, revealing significant reductions in particulate matter and contrail optical density and reflectivity with certain fuels.

Figure 2, Left: NRC ground emissions support during ECLIF3 test campaign. Right: NRC in-flight emissions and contrail measurement test campaign (right).

### *Future Directions*

In addition to $NO_x$, VOC and nvPM emissions, persistent contrails and contrail cirrus clouds are known to contribute to non-$CO_2$ emissions climate impacts. To further aid the international scientific community, NRC is either actively involved in, or formulating projects to solve emission related challenges:

- NRC is a collaborator with a European consortium of 10 partner organizations on Understanding Non-$CO_2$ Impact for Decarbonized Aviation (UNIC). The project aims to "*primarily further increase the scientific understanding related to the impact of aerosols on clouds as well as the contribution of aviation $NO_x$ emissions to climate change*."

1 DLR has also partnered with ONERA, AIRBUS, and CFM in the NEOFUELS-VOLCAN project, as well as with NASA, Boeing and GE during the ECO-Demonstator project to explore particle emissions and contrail formation from lean-burn combustors

2 Also known as nvPM, nonvolatile particulate matter

- NRC continues the development of emission measurement technologies and participation in ground tests to measure aircraft engine emissions
- NRC continues the development of calibration methods for the instruments used to quantify nvPM emissions, ultimately leading to improved characterization of the climate impacts associated with nvPM.
- NRC investigates measurement methods to quantify emissions of lubrication oil and other volatile particulate matter (vPM) in support of studies on the non-$CO_2$ climate impacts associated with lubrication oil (and other vPM) emissions from aircraft gas turbine engines.
- NRC will also Investigate the development of a ground facility for simulating contrails. This would allow more controlled and relatively cost-effective experiments on the ground to understand the effects of new fuels and engine technologies prior to undertaking more complex in-flight test campaigns, including ice nucleation studies.
- The renewal of NRC's in-flight emissions and contrails capabilities with our High-Altitude Atmospheric Research Aircraft[3] is also being investigated
- Aviation emissions are not occurring in isolation and often interact with the pre-existing complex ambient environment therefore it is important to put the aircraft emission measurements and monitoring into context. For that purpose, NRC is also focusing on Environmental research with airborne studies of the atmospheric composition and interactions including cloud formation processes. To further bolster our research capabilities in this area, NRC is renewing its aircraft capability with a Medium-Long range Aircraft Platform for Environmental Research (MAPLE) as part of the Government of Canada's commitment to revitalize and modernize NRC facilities
- The Arctic is the most sensitive region to climate change, and one of greater warming rate. For example, in Alaska and Western Canada, winter temperatures have increased by 3-4°C in the last 50 years. Black carbon fallout from aviation emissions exacerbates cryosphere melt, whilst contrail formation promotes atmospheric warming. These regions have disproportionately high throughput of intercontinental aviation traffic. Scientific studies in the Canadian Arctic are a priority for increased understanding. In future Arctic deployments, the NRC plans to study the formation of contrails at different altitudes during the Polar night of the Arctic winter.

## ONERA Insight (or CLIMAVIATION initiative in France)

The CLIMAVIATION initiative in France, which aims to re-engage the French community on the non-$CO_2$ emissions topic and bring a contribution to the efforts on non-$CO_2$ effects, is a five-year research program supported by the French government and carried out in partnership between ONERA and Institute Pierre Simon Laplace (IPSL).

Contrails is a first major axis of the initiative, for which a first goal is to set up a complete simulation of the whole life cycle of a contrail from ice crystal formation to fully developed contrail, allowing an in-depth investigation of the parameters influencing contrail properties and providing contrails characteristics for initializing climate models. Microphysics mechanisms leading to ice crystals formation are in particular studied for low soot emissions case, for which volatiles are a potential sources of condensation nuclei for water condensation. The resulting models are included in a detailed near-field simulation tools taking into account the detailed aircraft geometry and dynamics of the interaction between the engine plume and aircraft wake. Simulation is further extended up to 15 minutes behind the aircraft to extract the properties that serve as initial characteristics in the LMDZ-INCA global climate model (GCM) used for the climate impact assessment. This model has received a number of upgrades during CLIMAVIATION to improve the representation of ice supersaturated regions (ISSRs) in which contrails are likely to appear and persist. Representation of contrail and contrail-cirrus radiative effect is also investigated, the goal being to better understand and evaluate the uncertainties introduced at radiative model levels and

3 This aircraft has a suite of sensors to measure nvPM, volatiles, $NO_X$, $CO_2$ and ice particles. The aircraft platform needs to be versatile enough to obtain both near field and far field measurements and traverse throughout the contrail to get a holistic measurement in all regimes of the contrail, as current NRC cross-sectional measurements have shown significant non-uniformity throughout the contrail. With a renewed capability, the aim is to undertake studies to better characterize the cirrus transition process (0-60 minute aged contrails) and gather in-flight data to understand the impact of new fuels and engine technologies

through the simplifications that are necessarily done in GCM, such as, for example, neglecting 3D effects.

$NO_X$ influences radiative forcing through a complex chain of chemical reactions. First, $NO_X$ produces ozone through a photochemical process, which increases the oxidation capability of the atmosphere due to OH formation that produces a destruction of methane. The decrease of methane produces, on a longer time scale, a lower production of ozone and water vapor. These multiple mechanisms act in opposite directions. They are relatively balanced but with different time scales. Their combination results in a significant uncertainty on the final effect on radiative forcing. A first scientific issue is the significant discrepancy between model results, the origin of these differences being not understood. A second one is that the multiple possible reactions are not always represented. In particular, there are questions today regarding interactions with aerosols. There are also reactions within the aircraft plume that are not captured at the grid scale of climate models. Last, the effect of $NO_X$ depends on background concentrations and so on emissions from the other sectors[4].

Interactions between particles and clouds are today particularly uncertain and notoriously difficult to represent in climate models. Uncertainty on the effect is such that no estimate could be provided by David Lee in his synthesis of 2021. A first scientific question is what are the concentration, the size and nucleating properties of aerosols after hours of residence in the atmosphere, for which there would be a critical need for observations that are however quite difficult. Next question is how far these aerosols are transported horizontally and vertically. Accordingly, studies are carried out in CLIMAVIATION on removal mechanisms for black carbon in the atmosphere. Last question is how clouds respond to aviation aerosols and how aviation aerosols compete with other aerosols. This is investigated through LES simulation of cloud response to aerosol perturbations.

All the model improvements are integrated in the LMDZ-INCA model of IPSL in order to perform a global assessment of current aviation impact on climate. For this, a complete inventory of aviation emissions is being build based on the air traffic for 2024 and reference methodologies for fuel burn and emissions estimates. Effort is also developed for exploiting observation data from satellite or ground observations in order to validate tools. This include development of algorithms for automated detection of contrails on images.

Besides CLIMAVIATION, ONERA is also involved in a number of national and European projects, with a strong focus on the impact of the new fuels and low soot combustors on contrails[5].

## Conclusion

Long-term partnerships and international coordination are essential for advancing the understanding of non-$CO_2$ impacts in aviation. By sharing data and avoiding duplication of efforts, IFAR members can ensure effective use of resources, translating scientific knowledge into practical solutions and policy interventions to reduce emissions and their climate impacts.

Through these initiatives, IFAR members are committed to pioneering advancements in aviation emission research, contributing to global efforts in climate change mitigation, and fostering sustainable aviation practices for the future.

4 All these questions are investigated within CLIMAVIATION, and also in collaboration with other partners in European projects such as ACCACIA, to improve the modelling in LMDZ-INCA.

5 Impacts of hydrogen and SAF were investigated with Airbus and Safran in the VOLCAN and Cirrus $H^2$ projects. ONERA is now leading the UNIC European project, in collaboration with NRC and other partners, aiming to a better scientific understanding of the real-world emissions of aircraft at flight altitude and the specific role these aviation-derived non-$CO_2$ emissions (gaseous, volatile, and non-volatile particulates) play on contrail and contrail-cirrus formation and aerosol-cloud interactions. ONERA has also developed a micro-Lidar for in flight characterisation of contrails that is to be operated in the coming months