Exploring the Contribution of Short-Lived Climate Pollutants (SLCPs) Mitigation to ICAO's Long-Term Aspirational Goal

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Introduction

The aviation sector is rapidly growing with passenger air traffic expected to double in the coming decades. With this projected growth, the environmental impact of the sector shifts into greater focus. To date, the aviation sector has contributed to 2.4% of anthropogenic carbon dioxide (CO_2) emissions and about 4% of radiative forcing, when considering the climate impacts of both CO_2 and short-lived climate pollutants (SLCPs), such as nitrogen oxides (NO_X), particulate matter, and condensation trails (contrails).[1] As highlighted by the ICAO non-CO_2 symposium, while there is uncertainty in quantifying the exact impact of SLCPs, they do have a net warming impact and action should be taken towards mitigation.[2]

In 2022, the ICAO 41st Assembly adopted a long-term aspirational goal (LTAG) of reaching net-zero CO_2 emissions in international aviation by 2050. To chart the path towards this goal, numerous decarbonization roadmaps were developed by groups including industry, NGOs, and governments.[3] These roadmaps highlighted the mitigation levers needed to achieve net-zero, with over half of necessary reductions coming from sustainable aviation fuels (SAF), and the rest from a combination of fuel efficiency improvements, hydrogen-powered aircraft, operational improvements, and small reductions in flying as fuel costs increase.

When we consider the sector's progress over the past three years, despite substantial percentage growth year on year, SAF uptake remains low (about 0.3% of jet fuel in 2024), or about one-twentieth the CAAF/3 goal of 5% carbon emission reductions from alternative fuels in 2030.[4] Additionally, the introduction of hydrogen-powered aircraft has been delayed by manufacturers, and new aircraft types with significant fuel efficiency improvements are not expected to enter service until the mid-2030s. The current trajectory highlights the challenge with both achieving the LTAG and aligning with the Paris climate agreement if relying on only in-sector CO_2 mitigation. Based on these developments, the ICCT has been assessing the potential for Short Lived Climate Pollutants (SLCP) mitigation to contribute to aviation's climate goals.

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1 M Klöwer et al., "Quantifying Aviation's Contribution to Global Warming," *Environmental Research Letters* 16, no. 10 (October 1, 2021): 104027, https://doi.org/10.1088/1748-9326/ac286e.

2 ICAO, "Interactive Summary of the Symposium on Non-CO_2 Aviation Emissions," 2025, https://www.icao.int/Meetings/SymposiumNonCO2AviationEmissions2024/Pages/Summary.aspx.

3 IATA, "Aviation Net-Zero CO_2 Transition Pathways: Comparative Review," April 2024, https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/nz-roadmaps.pdf.

4 IATA, "Slow Growth in SAF Production," December 10, 2024, https://www.iata.org/en/pressroom/2024-releases/2024-12-10-03/.

2023 Emissions Inventory

The starting point to understand the potential climate impact of aviation in the future is to quantify contributions from all pollutants in the present. To do so, we used ADS-B flight trajectory data purchased from Spire to develop a global inventory of 2023 aviation emissions, including CO_2, NO_x, non-volatile particulate matter (nvPM), sulfur oxides (SOx), water vapor (H_2O), and contrails.[5] The European Centre for Medium-Range Weather Forecasts' (ECMWF) ERA5 HRES data set was used for meteorological data input, as atmospheric conditions are relevant for aircraft performance modeling and contrail lifetime simulations. The Python version of BADA3 (pyBADA) was used with pyContrails to model the quantities of each pollutant and calculate their effective radiative forcing (ERF).

The International Panel on Climate Change (IPCC) uses the Global Warming Potential (GWP) metric to compare the impacts of different pollutants, which quantifies the warming impact of a given pollutant relative to 1 tonne of CO_2 emissions. Here, we consider 2023 aviation emissions under 20- and 100-year timescales (GWP20 and GWP100) for perspective in reference to climate targets.

Under a 20-year timescale (Figure 1, left), the total climate impact of the sector could increase by over two times that of CO_2 emissions when including warming from SLCPs. This is in the lower range of potential SLCP impact when considering the range indicated in Lee et al. (2021), which could be nearly 7 times that of CO_2.[6] Under a 100-year timescale (Figure 1, right), CO_2 emissions appear to make up the majority of the sector's warming. However, SLCPs could add to this by almost 40%, and given the large uncertainty associated with contrail warming, even end up nearly tripling the sector's climate impact.

The warming of NO_x emissions and contrails appear to be similar in magnitude across both metrics, however, there is a much larger range associated with contrail impact, and our 2023 contrail ERF estimate of 17.3 mW/m^2 is at the lower end of the estimate from Lee et al. Additionally, there is uncertainty associated with whether aviation NO_x will have a net warming or cooling effect in the future, due to potential changes in background levels of atmospheric ozone and methane. Regardless of the metric being used, non-CO_2 emissions, particularly contrails, will likely increase the total climate impact of the sector. When expressed in GWP100, the climate impact of the year's aviation activity increases between about 12-280% when including non-CO_2 emissions.

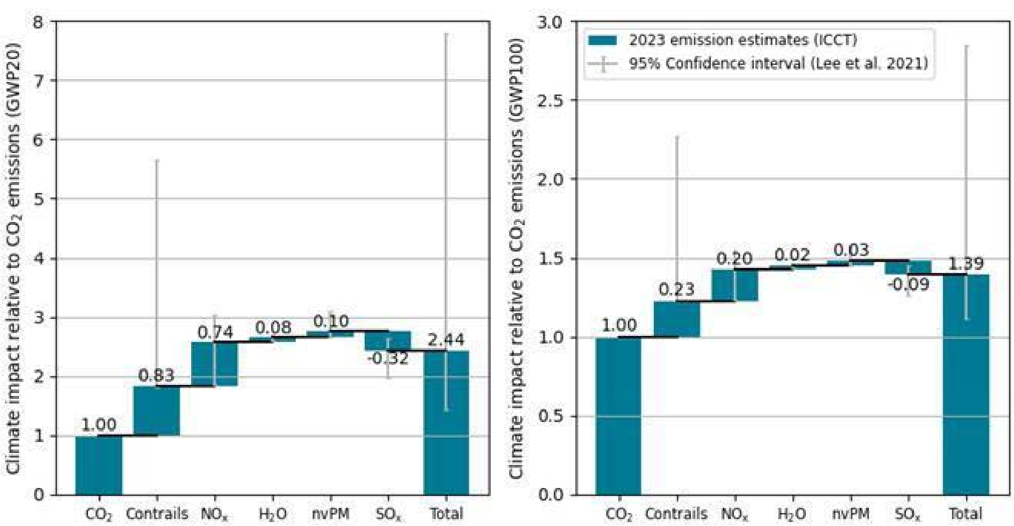

FIGURE 1: Climate impact from 2023 aviation emissions in GWP20 (left) and GWP100 (right)

5 Models used for each pollutant are as follows: BADA3 for fuel burn with constant emissions factors for CO_2, SOx, and H_2O, Boeing Fuel Flow Method 2 (BFFM2) for NO_x, T4/T2 method for nvPM, and CoCIP for contrails.

6 D.S. Lee et al., "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018," *Atmospheric Environment* 244 (January 2021): 117834, https://doi.org/10.1016/j.atmosenv.2020.117834.nitrogen oxides (NO_x

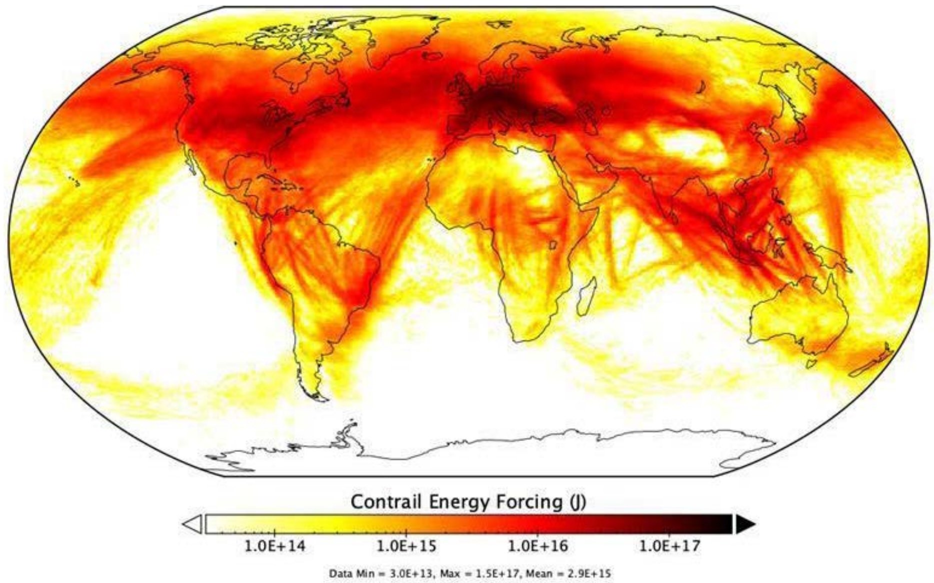

FIGURE 3: Global contrail energy forcing in 2023

Estimating the contribution of contrails to climate change remains challenging, in part because persistence and warming varies based on both climatological and meteorological conditions. To better understand regional differences in contrail impact, we plotted the energy forcing from contrails across all routes flown in 2023 in Joules (Figure 2). Here, we can see that most of the energy forcing occurs from flights departing Europe and North America flying over the North Atlantic region. If we categorize by World Bank income categories, over 95% of contrail warming is concentrated from departures from high- and upper-middle income countries, highlighting the need for developed aviation markets to take swift action to reduce their impact.[7]

Using this base emissions inventory, we are developing a model to project the potential warming contributions and surface temperature response from all aviation emissions through 2050 under different mitigation scenarios, including a business-as-usual case and various levels of CO_2 and non-CO_2 emissions reductions. While this work is still ongoing, we see the potential for targeted SLCP mitigation to buy time as other technologies mature and scale.

When considering the future growth of the sector and current progress made towards CO_2 emissions reductions, SLCP mitigation could present a way for the sector to reduce its climate impact while still allowing for sectoral growth. Some mitigation measures that are being pursued for CO_2 emissions can help to reduce SLCPs – namely SAF, which can reduce nvPM and contrail impact, and new engine technologies, which can reduce NO_x and nvPM emissions. Absolute, long-term reductions in radiative forcing will require new airframe, engine, and alternative fuel technologies, notably advanced SAF produced from cellulosic biofuels or e-kerosene. However, these will take time to penetrate the market. The most feasible short-term lever for SLCP control is contrail avoidance, which could provide a 73% reduction in warming for a 0.1% fleetwide increase in fuel burn.[8] While flight trials are ongoing, tactical avoidance in contrail-prone regions in the coming decades could allow for significant reductions in contrail climate impact with minimal fuel burn penalty.

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7 World Bank, "World Bank Income Groups," 2025, https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups.

8 A Martin Frias et al., "Feasibility of Contrail Avoidance in a Commercial Flight Planning System: An Operational Analysis," *Environmental Research: Infrastructure and Sustainability* 4, no. 1 (March 2024): 015013, https://doi.org/10.1088/2634-4505/ad310c.also known as contrails, contribute a substantial portion of aviation's overall climate footprint. Contrail impacts can be reduced through smart flight planning that avoids contrail-forming regions of the atmosphere. While previous studies have explored the operational impacts of contrail avoidance in simulated environments, this paper aims to characterize the feasibility and cost of contrail avoidance precisely within a commercial flight planning system. This study leverages the commercial Flightkeys 5D algorithm, developed by Flightkeys GmbH, with a prototypical contrail forecast model based on the Contrail Cirrus Prediction (CoCiP

Conclusions

Our findings highlight the value in targeted action from ICAO CAEP (Committee on Aviation Environmental Protection) towards non-CO_2 emissions – specifically, in monitoring impact, identifying climate metrics for impact assessment, and including their impact in aviation emissions trends projections.

Currently, the scope of the LTAG is limited to aviation's CO_2 emissions, and we believe this could be omitting a large and mitigable share of aviation's climate impact. Including non-CO_2 emissions in the LTAG would better reflect the full picture of aviation's total climate impact and could enable rapid reductions in aviation warming through contrail avoidance as new airframe, engine, and fuel technologies mature to address CO_2.