Literature review of aviation’s non-CO2 climate impacts and evaluation of existing metrics

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Glossary of terms

Aerosol-cloud	Aerosol-clouds are formed through clouds forming around small airborne particles. Aerosols can serve as cloud condensation nuclei (CCN), influencing cloud properties such as cloud droplet number concentration, cloud lifetime, and precipitation.
Air Navigation Service Providers (ANSPs)	Organisations responsible for managing air traffic within a specific airspace or region, including the provision of air traffic control services, navigation assistance, and communication support.
Alternative fuels	Fuels derived from renewable or non-petroleum sources, such as biofuels, hydrogen, synthetic fuels, and electric power, used to reduce dependency on traditional fossil fuels and mitigate environmental impacts.
Aromatics	A group of organic compounds containing a benzene ring structure, often found in fossil fuels.
Aviation forcing contributions	The impact of aviation-related emissions, including greenhouse gases, aerosols, and contrails, on global climate change and atmospheric composition.
CH_4 (Methane):	Chemical formula for methane, a potent greenhouse gas emitted from various natural and anthropogenic sources, including livestock farming, fossil fuel extraction, and waste management.
CO_2 (Carbon Dioxide)	A colourless, odourless gas, a trace gas in the Earth's atmosphere and also produced by the combustion of carbon-containing fuels in the context of aviation (but also a naturally occurring gas), primarily responsible for anthropogenic climate change and global warming.
Contrail	Short for "condensation trail," a visible trail of condensed water vapour and ice crystals formed behind aircraft engines under certain atmospheric conditions, such as low temperatures and high humidity.
Contrail Cirrus	High-altitude cirrus clouds formed from persistent contrails.

Cirrus Clouds	High-altitude clouds composed of ice crystals, typically found in the upper troposphere.
Climate-Charged Airspaces (CCAs)	CCAs refer to specific parts of the Earth's atmosphere that are significantly impacted by the aviation industry. These impacts are primarily due to the emissions from airplanes, which include greenhouse gases (GHGs), aerosols, and contrails (ice clouds formed by aircraft engine exhaust).
Cloud optical depth	A measure of the attenuation of light passing through a cloud due to reflection, absorption, and scattering by cloud droplets and ice crystals, influencing cloud radiative properties and climate feedbacks.
CoCiP	Standing for Contrail Cirrus Prediction Tool, CoCiP is a contrail model developed by DLR and recently implemented into the open-source python program, pycontrails. It uses weather data as an input to predict the formation, subsequent development, and total radiative forcing from contrails.
Collaboration for Climate Impact Partnership	An initiative aimed at addressing climate change challenges through collaboration between aviation stakeholders, policymakers, and researchers.
ERF (Effective Radiative Forcing)	A metric used to quantify the radiative imbalance caused by any external driver of climate, including changes in atmospheric composition, including greenhouse gas emissions, aerosol particles and clouds. ERF accounts for both tropospheric and stratospheric adjustments following the external forcing.
EF (Emission Factor)	A parameter indicating the amount of a specific pollutant emitted per unit of activity, such as fuel consumption, energy production, or vehicle mileage.
ECMWF (European Centre for Medium-Range Weather Forecast)	An independent intergovernmental organisation providing global weather forecasts, climate monitoring, and research services.
Formation Flight Impact	The potential reduction in fuel consumption and emissions achieved by aircraft flying in close formation, exploiting aerodynamic benefits and reducing drag.

Greenhouse effect	The trapping of infrared radiation in the Earth's atmosphere by greenhouse gases, leading to surface warming and climate change, similar to the warming effect observed in a greenhouse.
Global warming potential (GWP)	A measure of the relative contribution to the global energy imbalance over a specified time period of an emission of a kg of a greenhouse gas compared to emission of a kg of CO_2, serving as a basis for comparing climate impacts of different emissions.
H_2 (Hydrogen)	Chemical symbol for hydrogen gas, a clean and renewable energy carrier with potential applications in fuel cells, energy storage, and sustainable aviation fuels.
Ice nucleation (homogeneous/ heterogeneous)	The process of ice crystal formation in the atmosphere, facilitated by ice nucleating particles (INPs) acting as catalysts for ice formation, occurring through both homogeneous and heterogeneous pathways.
In-flight phase	The period during which an aircraft is airborne and operating between take-off and landing, encompassing various flight phases, including climb, cruise, descent, and landing.
Impacts and Science Group (ISG)	A multidisciplinary group of researchers and experts working under the ICAO Committee on Aviation Environmental Protection (CAEP), tasked with assessing the state of consensus in scientific research on the environmental impacts of aviation, including climate change, local air pollution around airports, and noise pollution.
ISSR (Ice Supersaturated Regions)	Regions of the atmosphere characterised by relative humidity with respect to ice exceeding saturation, providing favourable conditions for the formation of cirrus clouds and contrails.
Jet Fuel	A specialised type of aviation fuel used to power jet engines, typically derived from petroleum crude oil through refining processes.

Kerosene	A type of liquid hydrocarbon fuel used primarily in aviation and heating applications, characterised by its high energy density and stability.
LW (Longwave radiation)	Infrared radiation emitted by the Earth's surface, atmosphere, and clouds, contributing to the greenhouse effect and atmospheric heat retention.
Monitor Alert Parameter	An indicator used to monitor and assess environmental conditions, emissions, and atmospheric parameters relevant to aviation operations and local air pollution management.
NOx (Nitrogen Oxides)	A group of reactive nitrogen-containing gases, including nitrogen monoxide (NO) and nitrogen dioxide (NO_2), produced during combustion processes, contributing to air pollution, acid rain, and ozone formation.
Non-CO_2	Any climate forcings which are not CO_2 This includes greenhouse gases other than CO_2 emitted into the atmosphere, such as methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, playing significant roles in climate change and atmospheric chemistry. It also includes aerosol and contrail-cirrus.
Non-volatile particles	Particles emitted from aircraft engines that do not readily evaporate or sublimate in the atmosphere, contributing to aerosol formation, cloud microphysics, and air quality.
NO (Nitrogen monoxide)	A reactive gas molecule composed of one nitrogen atom and one oxygen atom, formed during combustion processes and atmospheric chemical reactions, contributing to air pollution and atmospheric chemistry.
N_2O (Nitrous oxide)	A potent greenhouse gas produced by natural and anthropogenic sources, including agricultural activities, industrial processes, and combustion, contributing to global warming and stratospheric ozone depletion.
nvPM (Non-volatile particulate matter)	Fine particulate emissions from aircraft engines primarily composed of non-volatile compounds, such as soot and metallic particles, with implications for air quality and human health.

Oxidative capacity of the atmosphere	The ability of atmospheric oxidants, such as hydroxyl radicals (OH), to degrade and remove pollutants and greenhouse gases from the atmosphere through chemical reactions.
Perturbation	A disturbance or deviation from the normal state, such as changes in atmospheric composition, weather patterns, or climate conditions, resulting from natural processes or human activities.
Pycontrails	Pycontrails is an open-source project and Python package for modelling aircraft contrails and other aviation related climate impacts.
RF (Radiative Forcing)	The net change in the Earth's energy balance caused by external factors, such as greenhouse gas emissions, aerosols, and solar radiation, influencing climate variability and long-term trends.
ReFuelEU	European Union initiative aimed at promoting the use of sustainable aviation fuels to reduce aviation emissions and mitigate climate change impacts.
RHice (Relative Humidity with respect to Ice)	The ratio of the actual water vapour content in the atmosphere to the maximum water vapour content that the air can hold at a given temperature, determining the likelihood of ice formation and cloud formation.
Synthetic kerosene (or e-kerosene)	A type of sustainable aviation fuel produced from renewable resources, such as biomass, waste, or carbon capture and utilisation technologies, offering a low-carbon alternative to conventional jet fuel.
Sustainable Aviation Fuel (SAF)	Renewable or low-carbon alternatives to conventional fossil-based aviation fuels, produced from biomass, waste, or synthetic processes, with the potential to reduce greenhouse gas emissions and environmental impacts from aviation.
Soot	Fine particulate matter composed of carbonaceous particles emitted from combustion processes, including aircraft engines, vehicle exhaust, and industrial sources, with implications for air quality, climate, and human health.

Stratosphere	The second layer of the atmosphere of the Earth, compositing stratified temperature layers; warmer towards the top of the stratosphere, and cooler towards the earth's surface.
SW (Shortwave radiation)	Solar radiation emitted by the sun in the form of near-IR (infrared radiation), visible light and ultraviolet radiation, influencing Earth's climate, weather patterns, and energy balance through absorption, reflection, and scattering processes.
Tropopause	The boundary layer between the troposphere and the stratosphere (layers of the earth's atmosphere), characterised by a sharp decrease in temperature with increasing altitude, serving as a dynamic barrier to atmospheric mixing and a key transition zone for climate processes.
Troposphere	The lowest layer of Earth's atmosphere, extending from the surface up to the tropopause, where most weather phenomena occur, and temperature decreases with increasing altitude.
UTLS (Upper Troposphere Lower Stratosphere)	The transition region between the troposphere and the stratosphere, spanning approximately 5 kilometres around the tropopause, characterised by distinct meteorological and chemical properties.
Weather reanalysis	A retrospective analysis of past weather observations and numerical weather model simulations, providing comprehensive datasets for climate research, meteorological studies, and environmental monitoring.
Water vapour	The gaseous form of water present in the atmosphere, playing a critical role in Earth's climate system as the most abundant greenhouse gas and a key component of the hydrological cycle

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1 Executive Summary

1.1 Purpose and scope of the report

There is growing concern over the environmental impact of aviation beyond just CO_2 emissions. Historically, and currently, the focus of environmental policies has predominantly been on CO_2 due to its substantial role in global warming, however, the aviation sector contributes to climate change not only through CO_2 emissions but also through a range of other emissions and atmospheric interactions that are less understood and only recently being considered in policy frameworks. This includes the non-CO_2 impacts of aviation such as contrails, nitrogen oxides (NOx), aerosols, and water vapour, which have complex and varied impacts on the Earth's climate system. This report aims to help address this critical gap in understanding and policy by compiling and analysing the current state of knowledge about the non-CO_2 impacts of aviation and reviewing and evaluating possible methods and metrics to measure and monitor their impacts.

Global air traffic has emitted 32.6 billion tonnes of CO_2 emissions between 1940 and 2018 and represents around 1.5% of total anthropogenic CO_2.[1] When non-CO_2 impacts and emissions are included, the sector is estimated to be responsible for 3.5% of total anthropogenic global warming by 2018.[2] Despite representing a minority of flights, routes over 1,500 km account for over 75% of GHG CO_2 emissions from aviation sector and also have significant non-CO_2 impacts.[3]

The report has been informed by the research and literature identified, which is heavily dominated by contrails studies, followed by those related to NOx. The report therefore has significantly more discussion around contrails, due to the greater amount of research currently being conducted in this area rather than because it is of greater or lesser importance than other impacts.

The analysis in this report will be used to help develop the Government's understanding of aviation's non-CO2 impacts and inform a wider research programme on non-CO_2 which is being led by the Department for Transport (DfT), Natural Environment Research Council (NERC) and Department for Business (DBT) and Trade.

The following approach was adopted:

- **Systematic assessment of literature:** A systematic assessment was undertaken on the current activities on aviation's non-CO_2 impacts, sourced from both academic research, industry insights and existing knowledge, all of which

[2] European Commission. (n.d.). Questions and Answers on the Fit for 55 Package. Available at: https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_4756
[3] European Parliament. (n.d.). Revision of the EU Emission Trading System for Aviation. Available at: https://www.europarl.europa.eu/legislative-train/package-fit-for-55/file-revision-of-the-eu-emission-trading-system-for-aviation#:~:text=In%202028%2C%20following%20an%20impact,fuel%20and%20point%20of%20departure.
[4] Transport & Environment. (2022). FAQ: Aviation non-CO2 measures in Fit for 55. Retrieved from https://www.transportenvironment.org/wp-content/uploads/2022/10/FAQ-Aviation-non-CO2-measures-in-Ff55.pd

have been consolidated into this report. This included understanding the potential causes of the formation and behaviour of contrails and cirrus clouds, the role of NOx emissions, and the effects of aerosols and water vapour linked to aviation activities. It further considered potential mitigations that have been proposed and/or tested to reduce non-CO_2 impacts.

- **Impact analysis:** The literature was further analysed to understand the relative effects of these non-CO_2 impacts on the Earth's climate. This included examining how these impacts interact with atmospheric components, contribute to greenhouse effects, and consequently affect global warming and climate patterns.
- **Methods and metrics analysis:** To support DfT with any potential future policy development, the current methods and metrics used to calculate non-CO_2 impacts were identified, both at an overall and on a flight basis, and assessed for their appropriateness as a use of a metric, with the aim of identifying a singular metric that could be used to measure non-CO_2 impacts.
- **Collation and review of current research and trials:** Current trials being undertaken globally were collated and reviewed to suggest the impacts of the trials and identify gaps in the research.
- **Identifying gaps and future directions:** Gaps in the current scientific understanding of the non-CO_2 impacts of aviation were summarised, and suggestions made for future research and policy analysis.

1.2 Key findings

The **key non-CO_2 impacts of aviation** are:

- **Contrail and contrail cirrus:** Contrail cirrus is considered to have a significant effect on the climate; however, it can be either cooling or warming. Whether a contrail is warming or cooling, and the magnitude of its net radiative forcing depends on a combination of factors. These include the time of day (e.g., at night there is less solar radiation which loses the cooling term of reflected light), the presence of clouds above or below the contrail, and contrail properties such as geometry (which in turn depends on the local wind shear), and ice crystal shape and size. The formation, persistence, and spread of contrails into cirrus clouds are subject to significant uncertainties. Factors such as the exact composition of aircraft exhaust, atmospheric humidity, and ambient temperature play critical roles in contrail development. Additionally, the extent to which these contrails impact the Earth’s radiative balance, particularly their contrasting effects of trapping outgoing longwave radiation versus reflecting incoming solar radiation, remains an area of active research and debate.
- **NOx:** The impact of nitrogen oxides (NOx) on the climate is uncertain due to their dual role in atmospheric chemistry. While NOx emissions contribute to ozone

formation (creating a warming effect), they also facilitate the breakdown of methane (having a cooling effect). The net impact of these processes is dependent on the location, altitude, and timing of the emissions, making it difficult to generalise their climate effects.[4] In general, for current engines as engine efficiency goes up (and CO2 emissions go down), the combustion temperature increases, and more NOx is formed and emitted. In other words, there is a risk of more CO_2 emissions with designs prioritising NOx reductions (including hydrogen combustion) and vice versa.[5] NOx emissions will not change materially in a transition from kerosene to SAF.[6]

- **Aerosol-radiation interactions:** Both soot and sulfur dioxide are types of aerosols which interact with solar radiation. Soot particles released from jet engines absorb radiation from the sun leading to a small positive RF; whilst sulfur dioxide, produced from the oxidation of sulfur (found in jet fuel) with oxygen, scatters radiation from the sun resulting in a negative RF. The latter is thought to dominate over the former.[7] [8] Whilst certain non-CO_2 impacts may have a net cooling impact, SO_2 causes additional issues such as the destruction of stratospheric ozone and the formation of acid rain.
- **Aerosol cloud interactions:** The role of aerosols emitted from aircraft engines in cloud formation and their subsequent impact on climate is another area marked by significant uncertainty. These interactions affect cloud properties and lifetime, with potential implications for both warming and cooling effects. However, the extent and magnitude of these impacts are not yet fully understood, largely due to the complex and variable nature of cloud physics and chemistry.

The **current data on non-CO_2 impacts**, especially concerning aerosol-cloud interactions and the full climatic implications of NO_x emissions, are fragmented and has significant uncertainties. Uncertainties have significant implications for climate modelling and policy development. Current climate models may not fully capture the transient and localised effects of non-CO_2 impacts, leading to gaps in our understanding and prediction of aviation's overall climate impact. Furthermore, the lack of precise quantification hinders the formulation of effective environmental policies and mitigation strategies targeting these impacts.

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[4] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740. https://doi.org/10.1039/D3EA00091E

[5] Quadros, F.D.A., Snellen, M. and Dedoussi, I.C. (2022) 'Recent and Projected Trends in Global Civil Aviation NOx Emission Indices', in. American Institute of Aeronautics and Astronautics Inc, AIAA. Available at: https://doi.org/10.2514/6.2022-2051.

[6] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740. https://doi.org/10.1039/D3EA00091E

[7] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. *Environmental Science: Atmospheres*, *3*(12), pp.1693-1740.

[8] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, p.117834.

Despite the uncertainties over the non-CO_2 impacts from aviation, several **mitigation measures have been proposed**, and in many cases trialled to reduce the impacts of these emissions. These can be grouped into the following types:

Alternative Fuels: Several alternative fuels are currently being considered, developed and trialled within aviation with the aim of reducing the CO_2 impacts. All alternative fuels show promise in reducing contrail formation; however, concerns remain over NOx emissions with hydrogen engines, due to the high burn temperatures. Using ammonia as a hydrogen fuel carrier to cool the compressor intercooler could reduce, or even eliminate NOx emissions, and could potentially lead to a 50%-99% reduction in climate impact (spanning CO_2, NOx, water vapour and contrail-related factors).[9] Using Sustainable Aviation Fuel (SAF) for all flights could reduce contrail formation, however using a higher percentage of SAF on the most warming flights (rather than a blanket percentage for all flights) can effectively reduce annual contrail forcing further. This would prove to be difficult in practice as separate storage and distribution of SAF from conventional kerosene would be impractical and expensive.[10]

Aircraft and engine design innovations: Improvements in aircraft design to enhance aerodynamic efficiency can lead to reduced fuel consumption and emissions. Research into new materials, wing designs, and overall aircraft architecture is ongoing. Recent engine design improvements have been focused on reducing CO_2 emissions, however the higher temperatures required to achieve this also result in higher NOx impacts. Advances in engine technology, such as higher bypass ratios and improved combustion efficiency, are aimed at reducing NOx and particulate emissions, without increasing CO_2 impacts.

Operational strategies: Non-CO_2 impacts including contrails from aircrafts could be reduced and prevented through relatively small deviations of flight plans, thus reducing their impact on climate change and global warming with some products already available with adopters of such solutions. Due to the nature of the changing flight direction, these strategies could lead to an increase in CO_2 emissions due to greater fuel burn; any benefit to non-CO_2 impacts need to be considered alongside any CO_2 increase.

A comprehensive approach encompassing technological innovation, operational changes, regulatory frameworks, and collaborative efforts is seen as essential for effectively mitigating the non-CO_2 impacts of aviation. While challenges remain, particularly in terms of technological feasibility and economic viability, these strategies collectively offer a pathway towards more sustainable aviation.

[9] Otto, M. et al. (2022) 'Ammonia As An Aircraft Fuel: Thermal Assessment From Airport To Wake', in. American Society of Mechanical Engineers (ASME). Available at: https://doi.org/10.1115/GT2022-84359.

[11] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, p.117834.

Assessing the non-CO_2 impacts from aviation involves a range of **methods and metrics**, each tailored to capture the specific characteristics and effects of these impacts. Unlike CO_2, where the metric of carbon footprint or CO_2-equivalent emissions is commonly used, non-CO_2 impacts require more varied and intricate methodologies due to their complex nature. The metrics are used to compare the impact of different emissions and forcings, typically quoted relative to CO_2, allowing for the consideration of trade-offs. However, equivalence (the ability to compare between impacts) is not uniquely defined, leading to variations in temperature outcomes depending on the metric and timescale used, and therefore using an equivalent metric could lead to adverse effects. Lee *et al*. (2021) found that the ratio of total CO_2-equivalent emissions to CO_2 emissions varies from 1.0 to 4.0, depending on the metric.[11]

Several metrics were evaluated, and pros and cons of each were identified. Due to this evaluation, it was concluded it is currently not possible to rely on a single metric; understanding the non-CO_2 impacts of aviation requires a multifaceted approach with diverse methods and metrics, each tailored to capture the distinct characteristics of these impacts. A different approach, using a suite of metrics, is therefore recommended allowing stakeholders to prioritise relevant metrics dependent on policy needs. This approach can serve as the foundation for an accreditation system for climate-mitigating decision-making protocols. It requires structured discussions on policy requirements and metric strengths and weaknesses, incorporating lessons learned from real-world planning and practice. By employing appropriate climate metrics and considering their strengths and limitations, policymakers and stakeholders can make informed decisions to mitigate climate change effectively.

1.3 Recommendations and next steps

The primary focus should be a coordinated effort to deepen the understanding of the complex effects of non-CO_2 impacts – this should include comprehensive studies on contrail formation, NOx emissions' impact on atmospheric chemistry, aerosol-cloud interactions, and the effects of water vapour. In order to achieve a robust understanding, enhanced modelling capabilities are essential to simulate these emissions' climate impacts accurately. This includes integrating advanced atmospheric chemistry models into climate simulations and improving the resolution and coverage of satellite and ground-based observational networks.

Further consideration should be given to:

- **Enhanced interdisciplinary collaboration:** **Foster closer collaboration between academia, industry, and government to address the multifaceted challenges posed by aviation's non-CO_2 impacts** (for example through the existing wider Non-CO_2 Research Programme). This could take the form of

[11] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, p.117834.

regular forums and workshops that bring together experts from academia, industry, and government to share knowledge, collaborate on research projects, and develop joint solutions.

- **Methods and metrics**: A suite of metrics should be developed, in collaboration with industry stakeholders to define the most appropriate metrics to be used both in terms of the policy they are being used to measure and in ability to be adopted and used by the industry.
- **Policy integration: There is currently no integrated policy framework that accounts for both CO_2 and non-CO_2 impacts.** Current policies tend to prioritise CO_2 emissions, thereby neglecting the substantial contribution of non-CO_2 impacts to global climate change. Incorporate non-CO_2 impacts into aviation climate policies, ensuring that these impacts are accounted for in regulatory frameworks and mitigation strategies. This could include conducting comprehensive assessments of existing aviation climate policies and regulations to identify gaps and opportunities for incorporating non-CO_2 impacts. It will also be key to collaborate with international organisations and governments to harmonise aviation climate policies and ensure a consistent approach to addressing non-CO_2 impacts.
- **Technological innovation: Encourage investment in research and development of new technologies and fuels that can reduce both CO_2 and non-CO_2** impacts from aviation through technology demonstration projects and pilot programmes. This should consider the ATI's recently published non-CO_2 roadmap[12] which will be used to inform the wider non-CO_2 research programme.
- **Comprehensive impact assessment: Prioritise the development of comprehensive models that can accurately assess the climate impact of various emissions (including both CO_2 and non-CO_2), considering the interdependencies and potential trade-offs**. These could be used to inform policy decisions and mitigation strategies, ensuring that they are based on a comprehensive understanding of the climate impacts of aviation.
- **Stakeholder engagement: Continue to engage with stakeholders across the aviation sector to ensure that the research and mitigation strategies align with industry capabilities and constraints**.
- **Regular monitoring and review: Establish a mechanism for regular monitoring and review of the progress in understanding and mitigating aviation's non-CO_2 impacts**, adapting strategies as new insights emerge. This will ensure that the latest scientific knowledge and best practices are incorporated into aviation climate policies and regulations.

[12] Advanced Technology Institute. (2024). Non-CO2 Technologies Roadmap. Available at: https://www.ati.org.uk/wp-content/uploads/2024/03/Non-CO2-Technologies-roadmap-FINAL-March-2024.pdf

- **<u>Research focus areas</u>:** There is already significant academic and industry research focus on non-CO_2 impacts, with notable emphasis on contrails and NOx emissions. However, there are also **substantial gaps in understanding and quantifying these effects accurately.** These gaps hinder the development of effective mitigation strategies and policies. Recommended research areas include:
  - **Estimating relative significance:** Increasing confidence in how different forcings from different non-CO_2 impacts compare would aid policy development.
  - **High accuracy models:** Developing accurate parameterisations of complicated processes that can be used in models is essential.
  - **Climate impact from contrails:** Improved representation of contrail properties, processes, and radiative transfer calculations are needed to reduce uncertainties.
  - **NOx:** Further work is required to understand the overall impact of nitrogen oxides (NOx) on the climate as they have both cooling and warming effects.
  - **Aerosol-cloud interactions**: Further work is required to consider the extent and magnitude of these impacts, which are currently not fully understood.
  - **Trade-off with CO_2**: Improved understanding of the overall climate impact for each non-CO_2 impact, and comparison between each so that the overall climate impact of any developed mitigations can be considered (e.g. where trade-offs are needed between different impacts, such as between CO_2 and NOx emissions).
  - **Atmospheric water vapour:** improved modelling and measurements of water vapour at aircraft altitudes, especially for ice super-saturated regions and contrail-cirrus formation.
  - **Alternative fuels (SAF and hydrogen):** Additional research needs to be undertaken on the impact of SAF and hydrogen on contrail cirrus and mitigation strategies for reducing soot emissions and water vapour.
- **<u>Tool development</u>:** Developing more robust tools for observations is necessary – as there remain ongoing challenges in observing and measuring aspects of non-CO_2 impacts. The importance of independent validation tools and improved global satellite validation to provide more accurate weather data has also been highlighted by this study.

The outcomes from this study reinforce the urgency of a multifaceted approach to understanding and mitigating aviation's non-CO_2 impacts. Addressing the identified research priorities and methodological developments will help stakeholders to work together towards a more sustainable and environmentally responsible aviation sector.

2 Introduction

2.1 Purpose and objectives of the report

Aviation is a significant contributor to climate change, accounting for 2% of global energy-related CO_2 emissions in 2022.[13] However, its impact extends beyond CO_2 emissions, with aircraft engines also emitting other gases and particulate matter that affect atmospheric properties. These non-CO_2 effects, such as nitrogen oxides (NOx), water vapour trails, and cloud formation, are estimated to contribute twice as much to global warming as aircraft CO_2 and were responsible for two-thirds of aviation's climate impact in 2018.[14] Despite their considerable impact, no measures are in place at regional or global levels to address aviation's non-CO_2 climate impacts (It is worth noting that NOx and nvPM (non-volatile particulate matter) are already regulated for air quality purposes, for example through the International Civil Aviation Organization (ICAO)[15]). This is a result of the number of uncertainties associated with these non-CO_2 impacts, including the complexity of atmospheric interactions, transient nature and variable impacts, and measurement challenges. The non-CO_2 impacts of aviation engage in intricate interactions within the atmosphere, affecting cloud formation, atmospheric chemistry, and radiation balance. These interactions are complex and not fully understood, making it challenging to accurately predict their overall impact on climate. The transient nature and variable impacts of non-CO_2 impacts, which depend on several factors, including atmospheric conditions, time of day, and geographical location also adds layers of complexity to modelling and predicting their overall effect on global warming. Furthermore, accurately measuring and collecting data on non-CO_2 impacts poses significant challenges, such as distinguishing between contrails and natural cirrus clouds or accurately quantifying the concentration of NOx and aerosols at various altitudes. These uncertainties have significant implications for climate modelling and policy development, hindering our ability to fully understand and mitigate aviation's overall climate impact.

The aviation industry is increasingly vocal about the significant challenge posed by non-CO_2 impacts of aviation on climate change objectives. For example, the International Air Transport Association (IATA) recently published a report[16] setting out the need to understand the formation and climate impact of contrails to develop appropriate mitigation measures. Moreover, the report outlines the need for collaboration between research and technological innovation, and a call for a policy framework to address aviation's non-CO_2 impacts.

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[13] International Energy Agency. (n.d.). Aviation. Available at: https://www.iea.org/energy-system/transport/aviation
[14] Transport & Environment. (n.d.). Airplane pollution. Available at: https://www.transportenvironment.org/challenges/planes/airplane-pollution/
[15] ICAO standards and recommended practices icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ENVReport2022_Art17.pdf
[16] IATA Aviation contrails and their climate effect- Tackling uncertainties and enabling solutions https://www.iata.org/contentassets/726b8a2559ad48fe9decb6f2534549a6/aviation-contrails-climate-impact-report.pdf

Leading UK and international academics have highlighted that aviation's non-CO_2 impacts could have significant impacts on the climate, however, large uncertainties remain and therefore have stressed the need for further research to be undertaken. As a result, in October 2023, DfT alongside the Natural Environment Research Council (NERC) and Department for Business and Trade (DBT) in partnership with the Aerospace Technology Institute (ATI), launched a multi-year non-CO_2 research programme. The programme has two funding streams and supports academic and industry led research as it recognises the need to further develop the underpinning science and reduce the current uncertainties, but also recognises the importance of developing and testing the technologies and the potential solutions to see if they achieve a positive outcome by reducing aviation's non-CO_2 impacts. The development of both of these areas are therefore vital for bettering the Government's understanding of aviation's non-CO_2 impacts, developing potential mitigations and informing any future policy development. The academic call for projects was launched last year and industry call for projects was launched in May 2024.

There are several technologies that could be used to mitigate non-CO_2 impacts of aviation including more efficient engines, alternative fuels, and improved air traffic management, however, more research is needed to develop and commercialise these technologies. The ATI recently published a roadmap describing the potential mitigation options for reducing aviation's non-CO2 impacts[17] which will be used to scope the call for industry projects.

Collaboration between industry and academia is also important and last year, a 'Non-CO_2 Task and Finish Group' was set up to bring together experts from industry and academia to help better understand aviation's non-CO_2 impacts and consider mitigation approaches.

The analysis in this report will be used to improve the Government's understanding of aviation's non-CO_2 impacts and inform the approach to the wider research programme.

2.1.1 Climate challenges

The non-CO_2 impacts of aviation present a number of climate challenges, including:

- **Contrails and cirrus clouds:** Contrails are long, thin clouds that form when water vapour from aircraft exhaust condenses in the cold, high atmosphere. Cirrus clouds are thin, wispy clouds that are made of ice crystals. Both contrails and cirrus clouds can trap heat in the atmosphere, contributing to climate change.
- **Nitrogen oxides (NOx):** Nitrogen oxides are a group of gases that are produced when nitrogen and oxygen in the air react at high temperatures. Nitrogen oxides can contribute to climate change by reacting with other chemicals in the

[17] ATI-Non-CO2-Technologies-Roadmap-Report-FINAL-March-2024.pdf

atmosphere to form ozone, a greenhouse gas and by affecting the atmospheric lifetime of methane.

- **Water vapour:** Water vapour is emitted from aircraft engines as a product of kerosene combustion along with CO_2. While it does absorb infra-red radiation, it is naturally present in much of lower atmosphere and is not considered an anthropogenic greenhouse gas. In the upper troposphere where commercial aircraft fly, it has the potential to increase contrail formation and, in the stratosphere, where water vapour levels are naturally very low, increases do cause a warming and it is considered to be a greenhouse gas.
- **Aerosol-radiation and Aerosol-cloud interactions:** Among the emissions from jet engines are aerosols, including soot and sulfur dioxide aerosols. Both of these cause a climate impact by interacting directly with solar radiation (aerosol-radiation interactions) - this results in a small positive RF for soot, and a negative forcing from the sulfur dioxide.[18] In addition, both soot particles (which have been inside contrails), and sulfate emissions, may subsequently go and affect other clouds - there is high uncertainty over what the overall RF is for these aerosol-cloud interactions.[19]

Data collection accuracy on contrail formation is problematic. Contrails can have a significant impact on the climate, but it is difficult to measure their impact accurately as they are often small and difficult to detect and can be easily confused with other types of clouds. Contrails and contrail cirrus can both cool the Earth's surface by reflecting incoming solar radiation or warm the Earth's surface by trapping outgoing terrestrial radiation, depending on various factors such as the time of day, the presence of other clouds, and contrail properties. Quantifying the net radiative forcing of contrails and contrail cirrus is complex and uncertain. Contrail cirrus can either increase natural cloud cover by providing additional ice nuclei or reduce natural cloudiness by competing for available water vapour in the atmosphere. This interaction further complicates the assessment of the climate impact of contrails and contrail cirrus.

The non-CO_2 impacts of aviation are a significant challenge to climate change mitigation. The complex nature of the chemistry means that the net effect of aircraft engine NOx emissions on climate remains uncertain because of their complex interaction with atmospheric chemistry, which is non-linear and highly dependent on other sources of emissions. The outcome of this is that there is no unique radiative forcing effect per unit NOx emission (on a global scale). Further, the effect of aircraft NOx emissions on ozone varies strongly with location, altitude, and time of emission.

[18] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. *Environmental Science: Atmospheres*, *3*(12), pp.1693-1740.

[19] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. *Environmental Science: Atmospheres*, *3*(12), pp.1693-1740.

Other challenges include the complex interactions between aerosols and radiation, as well as the uncertainties in modelling aerosol-cloud interactions. Soot particles emitted from jet engines absorb solar radiation, leading to a positive radiative forcing (RF) effect, while sulfur dioxide scatters solar radiation, resulting in a negative RF effect. However, the net effect of these interactions is uncertain, and the dominance of the cooling effect of sulfur dioxide over the warming effect of soot is not fully understood. The modelling of the RF resulting from aviation sulfate aerosols is also complex and uncertain, as it depends on various factors, including the number of ambient aerosols present during cloud formation. The interactions between sulfate aerosols and low-level liquid clouds are thought to have a cooling effect, but the extent and magnitude of these impacts are not yet fully understood due to the complexity of cloud physics and chemistry.

Climate models are often used to understand the non-CO_2 impacts of aviation. These models can simulate the complex interactions between the atmosphere, the oceans, and the land surface. However, the assumptions required to model a small-scale feature like contrails globally mean that it is difficult to draw a definitive conclusion using a climate model[20]. As is common with climate studies, the assumptions and uncertainties must be explored to gain useful insights.

Despite these challenges, there is a growing body of research on the non-CO_2 impacts of aviation which is collated in this paper. This research will help us to better understand the climate effects of aviation and inform the development of policies and technologies to mitigate these effects.

2.1.2 Regulatory and industry challenges

The regulatory and industry challenges related to the non-CO_2 impacts of aviation are complex and multifaceted. Currently, there is no regulatory framework specifically addressing these impacts in the UK, making it difficult for the Government to effectively monitor and mitigate them. The evolving scientific understanding of these impacts poses challenges in developing targeted regulations based on robust evidence. The global nature of aviation and the involvement of multiple stakeholders add further complexity, requiring coordination and cooperation at both national and international levels. Regulatory action by states on non-CO_2 has been limited to date. The main exception is the EU, who are currently developing a Monitoring, Reporting and Verification (MRV) system for gathering data on aviation's non-CO_2 impacts. Airlines will be required to monitor and report on emissions including, non-CO_2 from 2025 and the European Commission is required to submit a

[20] For example Lee et al., 2023, note that estimating the effective radiative forcing from contrails in Earth System Models (a high fidelity Global Climate Model – see reference below) has associated difficulties which include:- potentially having to use reduced complexity physics in radiative transfer calculations so that the simulation is not too computationally expensive.
- having to pick out the ERF signal (i.e the change in effective radiative forcing due to contrails) in the simulation from the 'noise', the natural variability of the modelled climate.,Energy.gov. (n.d.). DOE Explains...Earth System and Climate Models. Available at: https://www.energy.gov/science/doe-explainsearth-system-and-climate-models#:~:text=Earth%20system%20models%20and%20climate,comprehensive%20than%20global%20climate%20models.,Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. *Environmental Science: Atmospheres*, *3*(12), pp.1693-1740.

report, and, where appropriate and based on an impact assessment, a legislative proposal by December 2027 to expand the scope of the EU Emissions Trading System (EU ETS) to cover non-CO_2 effects.[21] Similarly, the ReFuelEU initiative also includes a MRV, which is due to be in place from August 2024, to monitor the level of aromatics, naphthalene and sulfur in jet fuel.[22]

The aviation industry in the UK is aware of several challenges in addressing the non-CO_2 impacts of its operations. One significant challenge lies in the high costs associated with implementing technologies and operational changes to reduce these impacts. Retrofitting aircraft with more efficient engines, utilising sustainable aviation fuels, and optimising flight operations require substantial investments, which can strain the financial resources of airlines and other industry players. Moreover, the lack of a level playing field in terms of regulations and incentives creates additional challenges. Currently, the non-CO_2 impacts of aviation are not subject to the same level of regulation as CO_2 emissions, leading to a lack of economic incentives for airlines to prioritise their reduction. Due to the lack of single metrics, challenges in predicting where contrails will form and, and uncertainty and complete understanding of non-CO_2 impacts, it is challenging to implement a robust economic incentive at this time.

The situation is further complicated by the need to consider trade-offs when developing mitigations for aviation's climate impacts. In particular CO_2 emissions are likely to be affected by measures taken to reduce the climate impacts of contrails or NOx. Systems need to be developed to help make decisions on how best to proceed which will require collaboration between government, different players in the aviation sector and scientists. They will also have to consider the parallel regulation of NOx and nvPM emissions in the landing and take-off cycle for air quality reasons.

2.2 Approach and methodology

The approach and methodology adopted for this report included a systematic approach to identifying and prioritising relevant academic and non-academic literature, a comprehensive literature review, and stakeholder engagement, which is further detailed in the appendix. The literature review focused on contrails, NOx, other non-CO_2 impacts and metrics, with a detailed search strategy and screening process to establish a relevant literature database, with search terms and screen agreed by the DfT. The literature review also considered further details of current major research programmes being delivered on this subject. Stakeholder engagement included a workshop to understand industry challenges and views on the non-CO_2 impacts of aviation and gather insights for non-CO_2 aviation metrics,

[21] European Parliament. (n.d.). Revision of the EU Emission Trading System for Aviation. Availiable at: https://www.europarl.europa.eu/legislative-train/package-fit-for-55/file-revision-of-the-eu-emission-trading-system-for-aviation#:~:text=In%202028%2C%20following%20an%20impact,fuel%20and%20point%20of%20departure.
[22] Transport & Environment. (2022). FAQ: Aviation non-CO2 measures in Fit for 55. Availiable ay: https://www.transportenvironment.org/wp-content/uploads/2022/10/FAQ-Aviation-non-CO2-measures-in-Ff55.pdf

policies, and implementation strategies. Further details of our methodology and stakeholder engagement outputs can be found in the appendix.

2.3 Report structure

This report comprises three parts: The first is a literature review of all existing research on aviation's non-CO_2 impacts; the second is an evaluation of the existing methodologies and metrics to measure and monitor the non-CO_2 impacts of aviation; the final section further explores identified gaps and provides details of international research currently being undertaken in this sector.

The literature review consolidates the existing research identified by this study in non-CO_2 impacts of aviation, the key findings to date, and where further research may be required, and how this could be most effectively implemented. The evaluation of existing methodologies to measure the non-CO_2 impacts of aviation builds oncurrent commitment and identifies, compares, and evaluates existing methodologies and metrics identified by this study, alongside methods to compare them to the measurement of CO_2 emissions.

3 Non-CO_2 impacts from aviation

3.1 Introduction

Aviation's contribution to climate change extends beyond CO_2 emissions. Non-CO_2 impacts such as those from NOx, water vapour, and particulate matter are significant contributors to climate change, potentially accounting for potentially two-thirds of the sector's net radiative forcing. Among these, contrails and contrail cirrus clouds are particularly noteworthy. Their impacts could match or exceed the climate impact of CO_2 emissions but are subject to even larger uncertainties. Another crucial aspect is NOx emissions, predominantly generated from high-temperature combustion in aircraft engines. These emissions significantly affect climate due to their interactions with ozone and methane, however, these impacts are complex and not fully understood.

In light of the domestic and global initiatives to decarbonise aviation, understanding non-CO_2 emissions and their climate impact is paramount. This chapter brings together and assesses the most up-to-date information on the climate impacts of non-CO_2.[23] It provides a comprehensive assessment of current research, both domestically and internationally, focusing on the complex relationship between aviation emissions and climate change. A major challenge is how to manage the trade-offs between different emissions including whether the state of knowledge is sufficient to do that with confidence.

The chapter is structured into two main sections. Section 3.2 delves into the current scientific understanding of key non-CO_2 impacts from aviation, encompassing contrails and contrail cirrus, NOx emissions, aerosol-radiation interactions and aerosol-cloud interactions. Following this, Section 3.3 assesses the significance of non-CO_2 emissions compared to CO_2 emissions in the context of aviation's overall climate impact. Furthermore, this chapter incorporates insights from the stakeholder workshop. Academics and stakeholders emphasise the importance of precision in defining and measuring the impact of aviation emissions, underlining the need for robust validation tools to ensure data accuracy.

The literature review reveals a consensus on the necessity for ongoing research in climate metrics, including counterfactual analysis, to holistically quantify the impact of aviation emissions. It's evident that while significant strides have been made in understanding and mitigating non-CO_2 impacts, considerable uncertainties remain. A comprehensive approach that equally considers CO_2 and non-CO_2 impacts is critical to addressing the aviation sector's overall climate impact effectively. Continuous research, technological innovation, and active stakeholder engagement are essential to navigate the complexities of aviation emissions and their climatic effects.

[23] As identified during and by this study

3.2 The non-CO_2 impacts from aviation and how they affect the climate

The Government has committed to delivering greener transport, including through the use of SAF. There has been early research to suggest that SAF provides benefits in reducing non-CO_2 impacts. However, there remain large uncertainties in respect of the impact of non-CO_2 from flight on the climate, and a lack consensus on how these are monitored and calculated in comparison to CO_2. This literature review brings together and assesses the most up-to-date information on the climate impacts of non-CO_2[24], and provides a basis for considering what metrics would be appropriate for evaluating their impact in comparison to CO_2.

Aviation affects the climate by emitting gases and particles that alter the atmosphere's "greenhouse" properties. This contributes to global warming and climate change. The measure of climate impact most commonly used is Radiative Forcing (RF), which is "the net change in the energy balance of the [Earth-atmosphere] system."[25] A slightly different measure, Effective Radiative Forcing (ERF), is referred to frequently in this document, is the metric adopted by the IPCC, and is the metric used in the well-known comparison of aviation forcing contributions in Lee *et al*, 2021 and Lee *et al,* 2023.[26] [27]

ERF captures the net radiative forcing change but also accounts for rapid responses from the atmosphere.[28] In the case of contrails for example, ERF in principle competes for the removal of water vapour with natural clouds.[29]

A primary pollutant from aviation is CO_2, a well-studied and quantified greenhouse gas. CO_2 has been assigned a "very high" level of confidence in its contribution to net anthropogenic forcing (which refers to the difference between the total radiative forcing due to human activities and the total radiative forcing due to natural factors). It represents the human-induced change in the Earth's energy balance, which can lead to climate change.[30] However, aviation also has several significant non-CO_2 impacts through its emissions of particles, water vapour, and NOx, affecting

[24] As identified during and by this study

[25] Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M.

[26] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

[27] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740. https://doi.org/10.1039/D3EA00091E

[28] Bickel, Marius and Ponater, Michael and Burkhardt, Ulrike and Righi, Mattia and Hendricks, Johannes and Jöckel, Patrick and Bock, Lisa (2023) *Climate impact of Contrail Cirrus: From conventional and Effective Radiative Forcings to Surface Temperature Change.* IUGG 2023, 11.-20. Jul. 2023, Berlin, Deutschland.

[29] Bickel, M., Ponater, M., Bock, L., Burkhardt, U., & Reineke, S. (2020). Estimating the effective radiative forcing of contrail cirrus. Journal of Climate, *33*(5), 1991-2005.

[30] Manchester Metropolitan University, David S. Lee (2018), The current state of scientific understanding of the non-CO2 effects of aviation on climate, https://assets.publishing.service.gov.uk/media/5d19c4fc40f0b609cfd97461/non-CO2-effects-report.pdf

aerosols, clouds, and atmospheric composition. These non-CO_2 impacts have a larger scientific uncertainty than the CO_2 impacts.

Global air traffic has emitted 32.6 billion tonnes of CO_2 emissions between 1940 and 2018 and represents around 1.5% of total anthropogenic CO_2[31]. When non-CO_2 impacts and emissions are included, the sector is estimated to be responsible for 3.5% of total anthropogenic global warming by 2018.[32] Despite representing a minority of flights, routes over 1,500 km account for over 75% of GHG CO_2 emissions from aviation sector, and this disproportionate contribution is also evident in non-CO_2 terms.[33]

The following sections set out the current scientific understanding of the key non-CO_2 impacts from aviation and their effect on the climate, as articulated in academic and non-academic sources.

3.2.1 Contrails and contrail cirrus

Condensation trails (or contrails) are line-shaped ice-crystal clouds generated in the wake of aircraft that fly through cold and humid parts of the upper troposphere/lower stratosphere (UTLS), called ice supersaturated regions (ISSR), typically between 8–13 km in altitude. Contrail ice crystals form around aircraft soot and other airborne particles onto which water vapour condensates and freezes, a process called ice nucleation. The size and composition of the ice crystals depends on trace emissions in the engine exhaust including aromatics and sulfur compounds.

The longer that ice supersaturation is maintained in the surrounding environment, the longer the lifespan of a newly formed contrail, so it can range from a few minutes to 24 hours. Some persistent contrails may even grow into larger, irregularly shaped ice clouds, so-called contrail cirrus, that may be indistinguishable from naturally occurring cirrus clouds.[34 35 36]

In common with naturally occurring cirrus cloud, contrails and contrail cirrus can both cool the Earth's surface by reflecting incoming solar radiation (shortwave radiation, SW) or warm the Earth's surface by trapping outgoing terrestrial radiation (longwave radiation, LW), in a process similar to the Earth's natural greenhouse gas effect. Whether a contrail is warming or cooling, and the magnitude of its net radiative forcing depends on a combination of factors. These include the time of day (e.g. at

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[31] [31] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

[32] DLR. (n.d.). One-third attributed to CO_2 emissions and two-thirds to non-CO_2 effects [Online]. German Aerospace Center. Available at: https://www.dlr.de/en/research-and-transfer/featured-topics/emission-free-flight/climate-impact-air-transport]

[33] DLR. (n.d.). Re-duc-ing the car-bon foot-print and cli-mate im-pact of con-trails [Online]. German Aerospace Center. [Accessed at: https://www.dlr.de/en/research-and-transfer/featured-topics/emission-free-flight/reducing-the-carbon-footprint-and-climate-impact-of-contrails]

[34] Minnis, P., Young, D.F., Garber, D.P., Nguyen, L., Smith Jr, W.L. and Palikonda, R., 1998. Transformation of contrails into cirrus during SUCCESS. *Geophysical Research Letters*, *25*(8), pp.1157-1160.

[35] Vázquez-Navarro, M., Mannstein, H. and Kox, S., 2015. Contrail life cycle and properties from 1 year of MSG/SEVIRI rapid-scan images. *Atmospheric Chemistry and Physics*, *15*(15), pp.8739-8749.

[36] Gierens, K.M. and Vázquez-Navarro, M., 2018. Statistical analysis of contrail lifetimes from a satellite perspective. *Meteorologische Zeitschrift*.

night there is less solar radiation which loses the cooling term of reflected light), the presence of clouds above or below the contrail, and contrail properties such as geometry (which in turn depends on the local wind shear), ice crystal shape and size. The orientation of the ice crystals to incident light, and their surface roughness, are also important factors.[37]

Quantifying the climate impact of contrails and contrail cirrus clouds is further complicated by their interaction with the hydrological process of natural cirrus clouds. Contrail cirrus can either increase natural cloud cover by providing additional ice nuclei that support formation of new ice crystals (see section below on aerosol-cloud interactions) or reduce natural cloudiness by competing for available water vapour in the ambient atmosphere.[38] [39] [40] [41]

Contrails will appear throughout this document and its conclusions more frequently than other impacts, as it is significantly more frequently studied than other impacts, both due to its uncertainty and because of the number and range of interventions that are possible to mitigate their impact, relative to the other non-CO_2 impacts. That is not to say it is more important than other impacts.

3.2.2 NOx (Nitrogen Oxides - the sum of NO_2 and NO)

NOx is emitted as an inescapable by-product of high temperature combustion in an aircraft engine. The high temperature splits the naturally occurring nitrogen in the air which then bonds with oxygen to form NOx. This happens in any high temperature combustor and is not dependent on fuel type. In general, for current engines as engine efficiency goes up (and CO_2 emissions go down), the combustion temperature increases, and more NOx is formed and emitted. In other words, there is a risk of more CO_2 emissions with designs prioritising NOx reductions and vice versa.[42] NOx emissions will not change materially in a transition from kerosene to SAF, meaning that the climate benefit of a transition is limited to the CO_2 contribution.[43]

The present-day climate effects for NOx and CO_2 based on ERF are estimated as 0.034 W m^{-2} for CO_2 and 0.017 W m^{-2} for NOx (Lee et al., 2021) though more atmospheric modelling and reporting of the ERF & RF for NOx is required.[44]

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[37] Kärcher, B., 2018. Formation and radiative forcing of contrail cirrus. *Nature communications*, *9*(1), p.1824.
[38] Boucher, O., 1999. Air traffic may increase cirrus cloudiness. *Nature*, *397*(6714), pp.30-31.
[39] Tesche, M., Achtert, P., Glantz, P. and Noone, K.J., 2016. Aviation effects on already-existing cirrus clouds. *Nature Communications*, *7*(1), p.12016.
[40] Burkhardt, U. and Kärcher, B., 2011. Global radiative forcing from contrail cirrus. *Nature climate change*, *1*(1), pp.54-58.
[41] Bickel, M., Ponater, M., Bock, L., Burkhardt, U. and Reineke, S., 2020. Estimating the effective radiative forcing of contrail cirrus. *Journal of Climate*, *33*(5), pp.1991-2005.
[42] Quadros, F.D.A., Snellen, M. and Dedoussi, I.C. (2022) 'Recent and Projected Trends in Global Civil Aviation NOx Emission Indices', in. American Institute of Aeronautics and Astronautics Inc, AIAA. Available at: https://doi.org/10.2514/6.2022-2051.
[43] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740. https://doi.org/10.1039/D3EA00091E
[44] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740. https://doi.org/10.1039/D3EA00091E

NOx emissions affect climate by increasing atmospheric ozone (O_3) and reducing methane (CH_4) levels, two important greenhouse gases, thus affecting the Earth's radiative balance. These two impacts of NOx depend on the location and time of year as well as the background composition of the atmosphere. The climate impacts associated with the O_3 and CH_4 responses to aircraft NOx emissions occur at different time scales, with the initial, warming formation of ozone followed by a longer-term cooling from the reductions of CH_4. The estimated impacts of NOx emissions on the climate system relative to other forcing agents are thus dependent on the choice of the climate metric and time horizon considered.[45]

The uncertainties associated with NOx emissions are greater than those associated with CO_2 emissions. This is partly a result of the limited amount of global atmospheric modelling which has been performed with the current generation of models and partly due to uncertainties in the complex, non-linear atmospheric chemistry and dynamics involved. More focussed modelling studies are needed to decrease uncertainties associated with the emission into NOx into the atmosphere and its subsequent removal, including the location of release and the future composition of the background atmosphere.

3.2.3 Aerosol-radiation interactions

Both soot and sulfate (SO_4) are types of aerosols which interact with solar radiation. Soot particles released from jet engines absorb radiation from the sun leading to a small positive RF (warming impact); sulfate particles, produced from the oxidation of sulfur (found in jet fuel) with oxygen, scatter radiation from the sun resulting in a negative RF (cooling impact) – the latter is thought to dominate over the former. It may be striking that certain non-CO_2 impacts may have a net cooling impact. It should be remembered however that SO_2 causes additional issues like the destruction of stratospheric ozone and the formation of acid rain.

3.2.4 Aerosol cloud interactions

Clouds, like contrails, absorb and reflect radiation. Aerosol emissions can influence the physical and radiative characteristics of clouds, leading to interactions known as aerosol-cloud interactions. Lee et al., 2021, and references within, provides a helpful overview of interactions between sulfate aerosols and clouds, some of which is summarised below.[46]

Sulfate aerosol can affect liquid-phase (low level) clouds by acting as a cloud condensation nuclei (CCN) – i.e. by acting as nuclei for the cloud particles to form – and the resultant increase in average particle size leads to an increase in the radiative forcing of the atmosphere. The modelling of the RF resulting from aviation

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[45] International Civil Aviation Organization (ICAO). (2022). ICAO Environmental Report 2022. [Online] Available at: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO%20ENV%20Report%202022%20F4.pdf

[46] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

sulfate aerosols depends on uncertain processes, as well as the number of ambient, or background, aerosol already present. If there are few background aerosols present during a cloud's formation, the radiative impact of the cloud has greater sensitivity to an increase in sulfate aerosol. Sulfate aerosol-cloud interactions on these low-level liquid clouds are thought to be negative. This topic is not unique to aviation as sulfate aerosol is released from other anthropogenic sources. Sulfate aerosol can also affect higher level ice clouds, by promoting freezing.

Soot particles only impact clouds (by being an ice nucleating particle – INP) if they have first been 'processed' by a contrail, meaning that they have previously been at a core of an ice crystal which has sublimated (Lee et al., 2023). This is because that process changes the chemistry of the soot particle and makes it more ice active. Therefore, the RF from contrails and these soot-cloud interactions are tied together. As soot particles age, they are coated by sulfuric acid which makes them unable to cause ice formation. A possible mechanism for how soot particles changes the RF through cloud interactions is laid out below:

- Soot can induce nucleation at lower humidities than certain other aerosols.
- Water vapour therefore may condense on these soot particles more than other aerosols.
- This leads to a lower number of larger ice particles
- These larger particles fall out of the cloud more easily
- This leaves the cloud with less ice.

Whilst the clouds are then less reflective (reducing cooling), they are also less able to absorb radiation from the earth's surface (reducing warming). A brief discussion on the magnitude of the forcings is provided in section 3.3.

3.2.5 Stakeholder workshop insights

Whilst the subject of the literature review and stakeholder workshop extended beyond contrails, the engagement during the stakeholder workshop held for this study primarily underscored the importance of precision and clarity in defining the impact of contrails on aviation emissions. Participants highlighted the imperative of narrowing down the timeline for contrail-induced warming, stressing the need for decision-makers to target specific periods to mitigate these effects effectively. Conversations focused on the importance of better understanding whether the impact should be measured immediately, over a period of time, or as an end state (which in turn drives the mitigation measures required). The participants further highlighted the critical need for independent validation tools to ensure the quality of data and processed results. This validation pertains significantly to contrails and weather forecast data.

3.3 How significant these non-CO_2 impacts are when compared to CO_2 emissions

Non-CO_2 impacts from aviation, such as NOx, water vapour, and particulate matter, have a significant impact on the climate, estimated to be contributing almost two-thirds of net radiative forcing.[47] However, there is significant uncertainty around this figure.[48] [49] While it is important to have confidence over the non-CO_2 impact when compared to CO_2 which is precisely known, as some mitigations to reduce non-CO_2 impacts may increase CO_2 emissions and the overall impact on the climate needs to be considered. There are different views on the interplay between non-CO_2 impacts and CO_2, and scientific debate should be expected and welcomed.

This section covers the major non-CO_2 impacts from aviation.

3.3.1 Contrails and contrail cirrus

There is generally academic and industry consensus that, when averaged over time, contrails and contrail cirrus have a significant net warming global effect.[50] [51] [52] .The IPCC's AR6 report cited Lee *et al.*, 2021, to give an ERF over 1750-2019 due to contrails of$60\ [20-100]\ mWm^{-2}$.[53] [54] [55],This is significant in comparison to Lee *et al.'s* CO_2 ERF estimate of 34.3 mWm^{-2}.[56] [57]

Contrails and contrail cirrus clouds are now recognised as one of the largest contributors to the global climate impact of the aviation sector, nearing or even surpassing the impact from CO_2 emissions. However, there are notable uncertainties, e.g. Lee *et al.*, 2023, noted that, whilst contrails are clearly observed, "the size of their radiative impact is still under discussion."[58] In their review, Lee et al,

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[47] International Civil Aviation Organization (ICAO). (2022). ICAO Environmental Report 2022. [Online] Available at: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO%20ENV%20Report%202022%20F4.pdf

[48] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

[49] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. *Environmental Science: Atmospheres*, *3*(12), pp.1693-1740. https://doi.org/10.1039/D3EA00091E

[50] Teoh, R., Engberg, Z., Schumann, U., Voigt, C., Shapiro, M., Rohs, S. and Stettler, M., 2023. Global aviation contrail climate effects from 2019 to 2021. *EGUsphere*, *2023*, pp.1-32.

[51] Burkhardt, U. and Kärcher, B., 2011. Global radiative forcing from contrail cirrus. Nature climate change, 1(1), pp.54-58.

[52] Minnis, P., Ayers, J.K., Palikonda, R. and Phan, D., 2004. Contrails, cirrus trends, and climate. *Journal of Climate*, *17*(8), pp.1671-1685.

[53] Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis,

[54] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, p.117834.

[55] This estimate rounded up Lee et al.'s values of 57.4 [17-98] mWm^{-2}, and was done due to uncertainty (it was asssessed with *low confidence*) and the value provided for the additional year of 2019 – Lee et al estimated an ERF for 1940-2018.

[56] This was estimated using 3 simple climate models (SCMs) which calculated CO_2 concentrations from emissions data.

[57] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

[58] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. *Environmental Science: Atmospheres*, *3*(12), pp.1693-1740. https://doi.org/10.1039/D3EA00091E

2023 also stress the different lifetimes of CO_2 and contrail cirrus make comparisons of their climate impacts difficult. This issue is also true for NOx and other short-lived climate forcers, but it is particularly acute for contrail cirrus which only exist for at most a day or so.

A number of estimates of global annual mean radiative forcing values for contrails are shown in Table 1 on the subsequent page. This quantity can be interpreted as the total change in energy over the course of a year in the earth/atmosphere, due to the presence of contrails, divided by the surface area of the earth, and the number of seconds in a year. Annual radiative forcing values will be different over different parts of the globe due to land mass areas the presence is applied over. However, the global annual figure is a helpful way to quantify the overall impact of contrails. The RFs and ERFs are shown here as they form the basis for the metrics discussed in Chapter 3.

An estimate from Lee *et al*., 2021 of the ERF of CO_2 for 2018 is included for comparison (as discussed previously, its uncertainty limits, indicated in square brackets, are less than the corresponding contrail forcing estimate). The CO_2 term was a function of the estimated concentration in the atmosphere (due to aviation), and so was estimated based off previous emissions. Comparing RF or ERF values for different years needs the caveat that year by year weather variability may significantly change the forcing[59], and so differences shouldn't be solely attributed to uncertainties in the scientific analysis.

[59] Teoh, R., Schumann, U., Gryspeerdt, E., Shapiro, M., Molloy, J., Koudis, G., Voigt, C. and Stettler, M., 2022. Aviation contrail climate effects in the North Atlantic from 2016–2021.

Table 1 Comparison of estimates of global mean forcing values for a given year. The latter two studies estimated RF, which was then converted into ERF using the ERF/RF scaling factor of 0.42 employed by Lee et al, 2021.

Study	Forcing Agent	RF, mWm^{-2}	ERF, mWm^{-2}	Year	
Lee et al, 2021[60]	CO_2	34.3 [31, 38]	34.3 [31, 38]	2018	This was estimated using three simple climate models (SCMs) which calculated CO_2 concentrations from emissions data. The bounds for the RF and ERF terms represent a 95% and 90% likelihood range respectively.
Lee et al, 2021[61]	Contrails	111.4 [33, 189]	57.4 [17, 98]	2018	Four previous estimates of annual contrail forcing were used and scaled based on a number of factors, to calculate the RF per unit km of flight distance.[62] This was used to estimate the forcing for 2018 based off inventory data, recording the total flight distance for 2018. The ERF here is not 0.42 of the RF as one of the 4 studies used to estimate the RF of 111.4 was treated as an ERF due to its modelling assumptions.The bounds in the RF and ERF values represent an estimated 70% percentage uncertainty, by considering relevant physical proceses. The ERF bounds do not account for the uncertainty in the ERF/RF ratio.
Bier & Burkhardt, 2022[63]	Contrails	44	18[64] (or 29 when scaling for 2018 air traffic[65])	2006	A global climate model, ECHAM5, was run with an incorporated contrail cirrus module (CCMod). The authors improved CCMod by including parameterisations for the effect of the wake vortex on the contrail's initial properties.

[60] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834
[61] ibid
[62] One of the studies used in the Lee et al, 2021, estimate was Bock and Burkhardt, 2016. Bier and Burkhardt, 2022 (see the next study in the table) ran a more detailed simulation and noted that the previous work was not as accurate. They achieved a lower value (44 vs 56 mWm^{-2}) and calculated that the Lee et al., 2021, estimate would reduce the RF by 6%, and the ERF by 4%.
[63] Bier, A., & Burkhardt, U. (2022). Impact of parametrizing microphysical processes in the jet and vortex phase on contrail cirrus properties and radiative forcing. *Journal of Geophysical Research: Atmospheres*, *127*(23), e2022JD036677.
[64] Here the RF to ERF conversion factor used was the same as that in Lee et al 2021, 0.42, which was estimated as an average of 3 studies.
[65] This value was calculated by using the scaling factor in Lee et al., 2021, for converting the 2006 RF estimate in Bock and Burkhardt (2016), to 2018
Bock, L. and Burkhardt, U., 2016. Reassessing properties and radiative forcing of contrail cirrus using a climate model. *Journal of Geophysical Research: Atmospheres*, *121*(16), pp.9717-9736.

Teoh et al, 2023[66]	Contrails	62.1	26.1	2019	CoCiP (Contrail Cirrus Prediction Model), as implemented in *pycontrails*, was run off ADS-B flight track data and ECMWF (European Centre for Medium-Range Weather Forecast) re-analysis[67] weather data.[68]

[66] Teoh, R., Engberg, Z., Schumann, U., Voigt, C., Shapiro, M., Rohs, S. and Stettler, M., 2023. Global aviation contrail climate effects from 2019 to 2021. *EGUsphere*, *2023*, pp.1-32.
[67] Weather data corrected by observations
[68] Marc Shapiro (2023) "pycontrails: Python library for modeling aviation climate impacts". Zenodo. doi: 10.5281/zenodo.7776686.

This table shows (a) the large central estimates for RF and ERF from contrails and hence their potential importance in mitigation measures; (b) the large associated uncertainties which currently add to the difficulty of assessing what mitigation measures should be taken; and (c) the differences between the recent estimates of RF and ERF made with different approaches.

The impact of ERF from contrails on global temperatures is an important issue regarding their climate impact. It may be assumed that the impact of a forcing agent on surface temperature scales exactly with its effective radiative forcing. However, this is in fact not necessarily the case.

Bickel et al., 2023, estimated the efficacy of contrail forcing on surface temperature change to be 0.4, which means that for a given ERF produced by both contrails and CO_2 emissions, the temperature change due to the contrails will be 40% of that caused by the CO_2 emissions.[69] This is only one estimate however and should not be taken as definitive. When presenting on this topic in the Eurocontrol Sustainable Skies Conference, 2023, Keith Shine, a climate scientist and meteorologist from Reading University, noted that this area needed much more research.[70]

3.3.2 NOx (nitrogen oxides - the sum of NO_2 and NO)

Aircraft combustors produce NOx, which creates ozone at cruise altitudes and, to a lesser extent, reduces the CH_4 atmospheric lifetime. NOx emissions from the aviation sector were 2.94 Mt, in 2018. This is expected to grow (with aviation) to 9.06 Mt by 2050 if no improvements are made in technologies and operational efficiencies including engine design. If such improvements were implemented, however, they may offer a reduction of 2.56 Mt by 2050 (i.e. to a predicted figure of 6.5Mt).[71]

The ICAO report also considered the impacts of NOx and highlighted that aviation NOx emissions from 1940 to 2018 have likely contributed to a net warming of the climate system. The report mentions a recent study suggests that the “net climate impact of aviation NOx might switch to a net cooling depending in particular on future background atmospheric composition, aircraft emissions, or when new processes or refined parameterisations are considered in the atmospheric chemistry models used to assess NOx emissions.” This is principally due to the changes that occur in the chemical composition and oxidative capacity of the atmosphere.[72] It should be noted that calculating changes in the oxidative capacity remains one of the major challenges of atmospheric chemistry with significant discrepancies between models.

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[69] Bickel, Marius and Ponater, Michael and Burkhardt, Ulrike and Righi, Mattia and Hendricks, Johannes and Jöckel, Patrick and Bock, Lisa (2023) *Climate impact of Contrail Cirrus: From conventional and Effective Radiative Forcings to Surface Temperature Change.* IUGG 2023, 11.-20. Jul. 2023, Berlin, Deutschland
[70] Shine, K. 2023. *Contrails Avoidance – Challenges.* Sustainable Skies Conference, Brussels
[71] International Civil Aviation Organization (ICAO). (2022). ICAO Environmental Report 2022. [Online] Available at: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO%20ENV%20Report%202022%20F4.pdf
[72] Skowron, A. et al. (2021) ‘Greater fuel efficiency is potentially preferable to reducing NOx emissions for aviation’s climate impacts’, Nature Communications, 12(1). Available at: https://doi.org/10.1038/s41467-020-20771-3.

The Global Methane Pledge is a voluntary agreement with over 155 members to take actions to contribute to a collective effort to reduce global methane emissions at least 30 percent from 2020 levels by 2030. The success of the Global Methane Pledge could lead to significant reductions in atmospheric CH_4.[73] The effect of NOx emissions on CH_4 and on O_3 is dependent on the background methane concentration and so the importance of NOx emissions (and hence the value of the metric) may change with time.[74]

Looking forward, a major change in NOx emissions will require a step change in propulsion with either lower temperature combustors or alternative powertrains e.g., to electric and possibly to H_2 engines which in turn will require a renewal of the global aircraft fleet. H_2 combustion engines still involve high temperatures combustion so lowering NO_x emissions should be taken into account in the engine design. It's worth noting that while this references the combustion of LH_2, there is also ongoing exploration and demonstration of hydrogen fuel cells in aviation, offering alternative avenues for emission reduction. Scenario modelling might be useful to inform decision-making on target emission factors.

3.3.3 Aerosol-radiation interactions

In their estimates of global RF from aviation, Lee et al., 2021, used ten estimates from the literature, obtained from eight different models of the global RF of soot and sulfate aerosols in aerosol-radiation interactions.[75] An ERF/RF ratio of 1 was used as the authors were not aware of any estimates of this parameter. The values derived were:

- Sulfate: -7.4 [-19, -3] mWm^{-2}
- Soot: $+0.9\ [0.1, 4.0]\ mWm^{-2}$

These values are fairly small compared to the other sources of forcing.

3.3.4 Aerosol cloud interactions

Lee et al., 2023, assess the magnitude of the ERF from aerosol-cloud interactions to be highly uncertain.[76] As stated in 2.1, they deem it likely that interactions between sulfate aerosol and clouds likely cause a negative forcing but note that whether the forcing from soot is positive or negative (warming or cooling) is uncertain. They report that Zhu and Penner, 2020, obtained a value of $-140\ mWm^{-2}$ but that it is

[73] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740. https://doi.org/10.1039/D3EA00091E

[74] A. Skowron, D.S. Lee, R.R. DeLeon, L.L. Lim, and B. Owen, Should we reduce aircraft emissions of NOx emissions for the sake of climate?, Nat., Commun., 2021, 12, 564, DOI: 10.1038/s41467-020-20771-3.

[75] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

[76] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.

sensitive to a range of factors. Other studies have found smaller values which could even be positive, i.e., warming.

Reducing the soot emissions from aircraft may reduce the RF of contrails (see 4.1), however Lee et al., 2023, note that since soot plays an important role in both contrail formation and aerosol-cloud interactions, that the RF impact of reducing soot emissions from jet engines is unclear.[77] They state that the combined effect of aerosol-cloud interactions and contrails could be a positive or negative ERF.

3.3.5 Stakeholder workshop insights

Stakeholders expressed an interest in a better understanding of the developments in climate metrics that precisely quantify the impact of aviation emissions, both CO_2 and non-CO_2 and that developments were still required. Suggestions were made to adopt a strategy involving counterfactual analysis (comparing with the course that would have been taken without an intervention taking place) to evaluate alternative outcomes. Counterfactuals will also help bring CO_2 alongside non-CO_2 into the wider climate frameworks and assess co-benefits / risks.

3.4 Conclusion

The examination of non-CO_2 impacts from aviation presented in this chapter underscores the complexity and significance of these emissions in shaping our climate. Section 2.1 discussed various non-CO_2 impacts, revealing their intricate interplay and diverse mechanisms of influence. From contrails to NOx emissions and aerosol interactions, each component contributes to the overall climate effects in unique ways.

The mechanisms through which non-CO_2 impacts climate can be complex: released soot particles, if processed by a contrail, may impact the optical depth of other clouds, and NOx emissions lead to warming and cooling impacts through different mechanisms.[78] Effective Radiative Forcing (ERF) is a helpful metric for getting closer to the climate impact by accounting for rapid changes in the atmosphere in response to emissions. Aerosol-radiation interactions do not appear to be large in magnitude and so potentially require less of a focus (but they are not negligible), whereas contrails and NOx, and to a greater extent soot-aerosol and aerosol-cloud interactions, have a more uncertain radiative impact. Sulfur plays an important role in both aerosol-radiation and aerosol-cloud interactions, resulting in a cooling impact in the former, and potentially the latter too. The interplay between CO_2 and non-CO_2 impacts also need consideration, for example, if the industry pivots to hydrogen aircraft in the coming years, whilst the CO_2 emissions will be significantly reduced,

[77] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.

[78] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

NOx emissions may well remain as contrails. Thus, research into non-CO_2 impacts is warranted not only for present day understanding and mitigation but also to give a clearer picture of the long-term impact of aviation as technologies change.

Section 2.2 further highlighted the significance of non-CO_2 effects from aviation, with estimates suggesting a greater impact than that from CO_2 itself. However, while the CO_2 impact on climate is known precisely, the non-CO_2 impacts include notable uncertainties, as shown in Figure 1. In the case of contrails, the estimated uncertainties are smaller than the central estimates, i.e., the net effect is a warming, but the central estimate for the ERF of contrails could be less than for CO_2 (Table 1). The relative impact of NO_x compared to CO_2 is significant, the present-day ERF of NOx is estimated to be 0.17 W m-2 compared to 0.034 W m^{-2} for CO_2. (Lee et al., 2021) (Section 2.1). The impact of NOx depends on many factors including latitude, altitude, season, and background composition of the atmosphere and more confidence in the estimates for the ERF would be gained by more modelling studies with a variety of models. Other non-CO_2 impacts exist such as aerosol-cloud and aerosol-radiation interactions, but their importance is thought to be smaller than those of contrail cirrus and NOx.

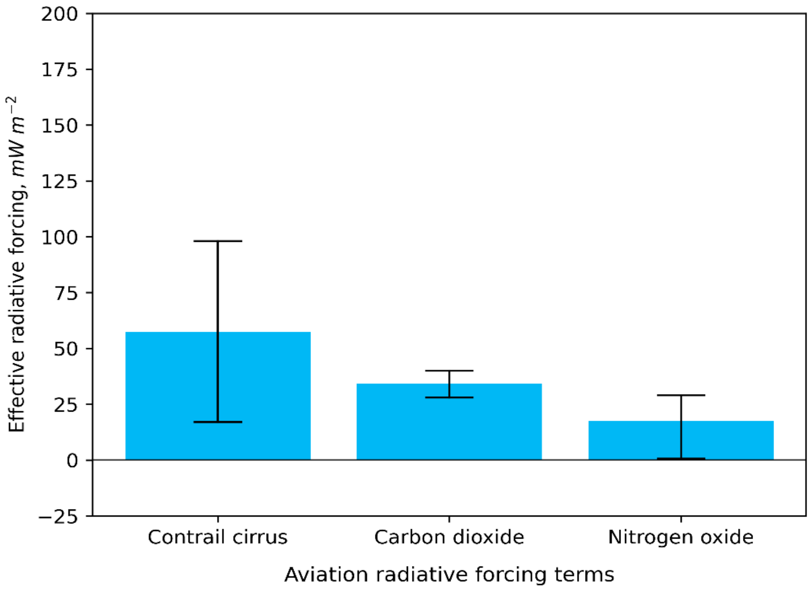

Figure 1: Chart describing the Effective radiative forcing (ERF) and uncertainties (error bars) of various non-CO_2 impacts (Reproduced from Lee et al, 2021)

Moreover, in the stakeholder workshop, stakeholders primarily emphasised the significance of precision and clarity in defining contrail impact on aviation emissions and suggested narrowing down timelines for mitigation. They stressed the need for independent validation tools for data quality, particularly regarding contrails and weather forecast data. Stakeholders also expressed interest in advancing climate metrics to quantify CO_2 and non-CO_2 emissions accurately.

4 Mitigation strategies and challenges

4.1 Introduction

In response to the climate challenge posed by non-CO_2 impact, scientists and industry stakeholders have developed multiple potential solutions to manage emissions and contrail formation in flight operations and broader mitigation measures.

This chapter navigates a diverse array of mitigation measures that have been explored to address aviation's non-CO_2 impacts. The following sections 4.2 to 4.8 span from alternative fuels (sustainable aviation fuel, hydrogen, ammonia) to aircraft and engine design, optimised flight planning, in-flight avoidance, lower flight, daytime flight only, and formation flights. These explored mitigation options vary across multiple dimensions including the timing of an intervention, technologies utilised, ease of application, technological readiness, and potential effectiveness, in addition to varied strengths and weaknesses, dependencies, suppliers and adopters. Similar to the impact findings, much of the activity has been on managing contrail formation as opposed to other non-CO_2 impacts.

The exploration of alternative fuels such as SAF and hydrogen has opened potential pathways to reduce aviation's climate impact. These fuels show promise in lowering both CO_2 and non-CO_2 impacts. However, challenges persist in their widespread adoption, including production and distribution complexities, and potential unintended effects like increased contrail formation. Moreover, innovations in aircraft and engine design also offer opportunities for reducing non-CO_2 impacts. Nevertheless, these advances must balance reductions in non-CO_2 impacts with potential increases in CO_2 emissions, and they face technological hurdles. Furthermore, strategies such as optimised flight planning, in-flight avoidance and lower flight altitudes demonstrate effectiveness in reducing contrail formation. These approaches, though promising, require advanced atmospheric modelling and add operational complexity. It should be noted that electric engines would reduce the non-CO_2 impacts substantially, whether batteries or fuel cells are used as the power source. This makes then a desirable approach from the perspective of reducing non-CO_2 impacts as well as from that of CO_2 reductions.

Furthermore, section 4.9 draws upon insights from stakeholder workshop, revealing a consensus on the crucial role of leveraging existing technologies to earnestly reduce emissions and their adverse effects. Stakeholder discussions highlight the importance of environmentally optimised flight planning over purely economic considerations. Despite resistance to action on contrail management primarily due to scientific uncertainty, fuel burn penalty and the lack of a driving force for change, the literature review of mitigation options, suggests a reasonable confidence and consensus around the case for targeted interventions at this point.

4.2 Mitigation option: Alternative fuels

Alternative fuels such as Sustainable Aviation Fuel (SAF) and hydrogen have been explored as potential solutions to mitigate the climate impact of aviation. SAF is a type of jet fuel which is produced from sustainable feedstocks, including two main categories: biofuels and synthetic fuels (also known as e-fuels, or Power-to Liquid (PtL) fuels). Biofuels are derived from sustainable biomass sources, such as used cooking oil, animal waste fat, municipal solid waste and agricultural residues. Synthetic fuels (e- fuels or PtL fuels) are synthesised from hydrogen and carbon dioxide (CO_2), which can originate from various sources. One climate-optimal method for producing e-fuels is through the use of green hydrogen (hydrogen produced by the electrolysis of water, using renewable electricity) and CO_2 captured from the atmosphere using renewable electricity.[79] SAF is a drop in fuel that can be used within conventional aircraft, whilst hydrogen will require aircraft using a different powertrain.

A particular benefit of these solutions is that they apply to all aircraft using alternative fuels without need for tactical intervention. However, there are significant dependencies on the capacity for large scale change in the fuel production and distribution industry for the sector, including battery-electric for smaller aircraft.

4.2.1 Sustainable Aviation Fuel (SAF)

There are several suppliers of SAF with many airlines starting to adopt the fuel. Scaling up will be challenging and the UK SAF mandate, which is expected to come into force in 2025, will require at least 10% of jet fuel supplied in the UK to be SAF by 2030 and as such understanding the total climate benefits of the transition will be important.

There has been some research and modelling to date. For example, in their modelling study, Teoh et al., 2022, found that the use of 100% SAF on a dataset of 477,923 flights travelling over the North Atlantic led to a 5% increase (relative to 0% SAF) in the length of persistent contrails due to the higher water vapour emissions of SAF compared to conventional jet fuel.[80] However, the mean contrail lifetime dropped by 15% and importantly the net RF dropped by 43.5%.[81] The authors note that their simulations remain in the soot-rich region even with 100% SAF (see section 4.2 for the relevance of this). The use of SAF could also help reduce the aromatic content in jet fuel, which could help cut air pollution and reduce the non-CO_2 climate impacts from contrail cloudiness.

Although SAF has the potential to be a significant step towards decarbonising the aviation industry, it alone is not sufficient to address the full spectrum of aviation's

[79] Transport & Environment. (n.d.). New Technologies - Challenges & Solutions for Planes. [Online] Available at: https://www.transportenvironment.org/challenges/planes/new-technologies/
[80] Teoh, R. et al. (2022) 'Targeted Use of Sustainable Aviation Fuel to Maximize Climate Benefits', Environmental Science & Technology, 56(23), pp. 17246–17255. Available at: https://doi.org/10.1021/acs.est.2c05781.
[81] Teoh, R. et al. (2022) 'Targeted Use of Sustainable Aviation Fuel to Maximize Climate Benefits', Environmental Science & Technology, 56(23), pp. 17246–17255. Available at: https://doi.org/10.1021/acs.est.2c05781.

environmental impacts due to insufficient supply and not currently achieving zero CO_2 and non-CO_2 impacts.[82] SAF reduces the contrail's net radiative forcing due to lower emissions of non-volatile particles[83], while low aromatic SAF blends can significantly reduce soot and ice number concentrations by 50%-70%, although the ice crystal size was found to increase.[84] The contrail lifetime will therefore be much shorter. Another measurement indicates that low-aromatic SAF blends decrease the ice particle numbers, extinction coefficients, optical depth, and climate impact from contrails.[85]

Using SAF on specific flights that contribute the most to global warming can further effectively reduce annual contrail radiative forcing (strongly warming contrails in this region are generally formed in wintertime, close to the tropopause, between 15:00 and 04:00 UTC, and above low-level clouds);[86] the greatest effect could be seen by using more SAF on the most warming flights, rather than as an average However, separate storage and distribution of SAF from conventional kerosene would be impractical and expensive and mandates such as the SAF mandate requires all aircraft to use a fixed amount (percentage) of SAF.[87]. Teoh et al., 2022, modelled that using 50% SAF blends on the top ~ 2% of the most warming flights over the North Atlantic could reduce the annual contrail energy forcing (EFcontrail) and the total energy forcing (EFtotal – this accounts for CO_2 emissions) by ∼10% and ∼6%, respectively. In contrast, using 1% SAF blends in all transatlantic flights has the potential to reduce the EFcontrail and EFtotal by ~ 0.6%. The energy forcing metric is strongly related to radiative forcing – in this study the radiative forcing, RF, was calculated using CoCiP and EF contrail was calculated by integrating this radiative forcing with respect to the contrail area and lifetime. The reduction of soot through the use of SAF does not necessarily mean that contrails will not form, as other particles may be activated to be nucleation sites and thus cores of ice crystals. More insight into the how SAF are made and what their net carbon emission is required, using approaches such as Life Cycle Analysis so that the full lifecycle emissions can be considered.

In addition, use of hydrocarbon-based fuels (kerosene and SAF) with reduced impurities (e.g., aromatics), can potentially reduce non-CO_2 impacts by decreasing soot emissions, leading to fewer ice crystals and contrail RF (see section 3.3.1 for

[82] International Civil Aviation Organization (ICAO). (2022). ICAO Environmental Report 2022. [Online] Available at: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO%20ENV%20Report%202022%20F4.pdf
[83] Kärcher, B. (2016) 'The importance of contrail ice formation for mitigating the climate impact of aviation', Journal of Geophysical Research, 121(7), pp. 3497–3505. Available at: https://doi.org/10.1002/2015JD024696.
[84] Voigt, C. et al. (2021) 'Cleaner burning aviation fuels can reduce contrail cloudiness', Communications Earth & Environment, 2(1), p. 114. Available at: https://doi.org/10.1038/s43247-021-00174-y.
[85] Bräuer, T. et al. (2021) 'Reduced ice number concentrations in contrails from low-aromatic biofuel blends', Atmospheric Chemistry and Physics, 21(22), pp. 16817–16826. Available at: https://doi.org/10.5194/acp-21-16817-2021.
[86] Atmospheric Chemistry and Physics. (2022). Title of the Document. Availiable at: https://acp.copernicus.org/preprints/acp-2022-169/acp-2022-169.pdf
[87] Transport & Environment. (n.d.). Jet Fuels - Challenges for Planes. [Online] Available at: https://www.transportenvironment.org/challenges/planes/jet-fuels/

further details on the associated uncertainty).[88] For example, hydrotreating kerosene may reduce aromatic contents and naphthalene by 8-10%.[89]

Hydrogen as an alternative fuel

Contrail cirrus is thought to have a larger contribution and uncertainty to the climate impact for liquid hydrogen as compared to conventional jet fuel as demonstrated in real world trials. As shown in the research of Miller, Chertow and Hertwich (2023), the contrail cirrus contributes to 81 ± 31% and 32 ± 7%, respectively, of the climate impact associated with the combustion of liquid hydrogen and conventional jet fuel.[90] Hydrogen combustion in flight could contribute to greater contrail formation due to increased water vapour emission. However, the effects could be counteracted by the absence of particle emissions that facilitate ice nucleation. Hydrogen combustion in flight could also cause higher NOx impacts due to the temperature of combustion.

The fuel production pathway design and flight pathway selection are critical to mitigating the impacts associated with liquid hydrogen. This is because different hydrogen production pathways may have varying climate impact from hydrogen production to combustion, with some even exceeding those of conventional jet fuel. Additionally, selecting the flight pathways that avoid areas prone to contrail formation can help mitigate the contrail formation.[91]

4.2.3 Ammonia as an alternative fuel

Ammonia is being regarded as a potential alternative to the fossil fuel, which can be potentially used as aviation fuel through several ways, including direct combustion, blending with hydrogen, utilisation in fuel cells, or as a hydrogen carrier. [92]

Ammonia serves as a hydrogen carrier, i.e., instead of being directly combusted, it is catalytically cracked into hydrogen, with the latter as the fuel.[93] Therefore, ammonia encounters the same challenge and advantage in contrail mitigation in a similar manner to hydrogen. Hydrogen combustion lacks soot particles that could serve as nucleation sites for condensation and ice formation, reducing contrails. Additionally, liquid ammonia (at approximately -33°C) required for selective catalytic reduction (SCR) can pass through a heat exchanger to condense water from the exhaust, decreasing water vapour pressure and further reducing contrail formation. As indicated in the study of Otto, M. et al. (2022), ammonia could simultaneously cool the compressor intercooling, delivering chilled air for NOx elimination, and condense

[88] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, p.117834.
[89] Transport & Environment. (n.d.). Non-CO2 Effects of Airplane Pollution. [Online] Available at: https://www.transportenvironment.org/challenges/planes/airplane-pollution/non-co2-effects/
[90] Miller, T.R., Chertow, M. and Hertwich, E. (2023) 'Liquid Hydrogen: A Mirage or Potent Solution for Aviation's Climate Woes?', Environmental Science and Technology, 57(26), pp. 9627–9638. Available at: https://doi.org/10.1021/acs.est.2c06286.
[91] Miller, T.R., Chertow, M. and Hertwich, E. (2023) 'Liquid Hydrogen: A Mirage or Potent Solution for Aviation's Climate Woes?', Environmental Science and Technology, 57(26), pp. 9627–9638. Available at: https://doi.org/10.1021/acs.est.2c06286.
[92] Fullonton, A., Jones, C., and Larkin, A. (2023) 'The Potential Role of Ammonia as a Low Carbon Aviation', University of Manchester. Available at: https://www.aef.org.uk/uploads/2024/01/AEF_TYNDALL_Ammonia_report_FINAL_PDF.pdf
[93] Spatolisano, E. et al. (2023). 'Ammonia as a Carbon-Free Energy Carrier: NH3 Cracking to H2', Industrial & Engineering Chemistry Research, 62(28), 10813–10827. https://doi.org/10.1021/acs.iecr.3c01419

water vapour in the emission to minimise contrail formation and therefore provide a potential climate benefit potentially leading to a 50%-99% reduction in climate impact (integration of CO_2, NOx, water vapour and contrails).[94]

Furthermore, in comparison to hydrogen, ammonia offers several advantages concerning volumetric energy density, safety, and the supply chain. Ammonia can stay in a liquid state across a broader temperature range, contributing to enhanced safety, reduced challenges in airport integration. Furthermore, ammonia already has a robust and mature supply compared to hydrogen. Additionally, liquid ammonia carries more hydrogen per unit volume than liquid hydrogen, offering storage benefits within the wings. [95]

However, similar to hydrogen, ammonia integration would require a novel fuel system for it to be properly conditioned and distributed. Modifications are also necessary to facilitate fuel combustion and reduce NOx emission. [96] When combusted, ammonia (NH_3) produces NOx through the thermal equilibrium mechanism (as for kerosene, SAF or H_2) and, to a lesser extent, from the N in the ammonia itself.

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[94] Otto, M. et al. (2022) 'Ammonia As An Aircraft Fuel: Thermal Assessment From Airport To Wake', in. American Society of Mechanical Engineers (ASME). Available at: https://doi.org/10.1115/GT2022-84359.
[95] Otto, M. et al. (2022) 'Ammonia As An Aircraft Fuel: Thermal Assessment From Airport To Wake', in. American Society of Mechanical Engineers (ASME). Available at: https://doi.org/10.1115/GT2022-84359.
[96] Otto, M. et al. (2022) 'Ammonia As An Aircraft Fuel: Thermal Assessment From Airport To Wake', in. American Society of Mechanical Engineers (ASME). Available at: https://doi.org/10.1115/GT2022-84359.

Table 2: Alternative fuel types and their impact and challenges.

Fuel Type	Description	Impact	Challenges
SAF	Drop-in fuel, categorised into biofuels (derived from renewable biomass) and synthetic fuels (synthesised from H_2 and CO_2 using renewable electricity)	Potential to reduce contrail's net RF, lowers emissions of non-volatile particles, reduces aromatic content in jet fuel, and cuts air pollution.	Limited supply. For greater impact, separate storage and distribution is impractical and expensive.
Hydrogen combustion as an alternative fuel	A fuel requiring aircraft with a different powertrain, potentially increasing the formation of contrails.	Potential negative climate impact due to increased contrails formation.	Uncertainty of climate impact for increased contrail formation.
Ammonia as an improved fuel	Ammonia can be potentially used as aviation fuel through several ways, including direct combustion, blending with hydrogen, utilisation in fuel cells, or as a hydrogen carrier.	Potential climate benefit due to NOx reduction and water vapour condensation reducing contrails	Technological advancements and resolution of safety issues around toxicity needed
Hydrogen fuel cell	Hydrogen for fuel cells is produced. Fuel cell aircraft produce electricity using a fuel cell powered by hydrogen	Only emit water vapour and warm air when used (emissions are from production)	Investment required for refuelling infrastructure. Limited availability of green hydrogen

4.2.4 Summary

In summary, while SAF, hydrogen and ammonia offer potential benefits in reducing the climate impact of aviation, challenges such as limited SAF supply and uncertainties surrounding hydrogen's climate impact need to be addressed. Further research and technological advancements are necessary to fully realise the potential of these alternative fuels in mitigating contrail formation and climate impact.

4.3 Mitigation Option: Aircraft and Engine Design

The literature review has identified several case studies in which improving fuel efficiency and aircraft designs have been cited as potential solutions for addressing aviation's non-CO_2 impacts. However, the scientific uncertainty around the climate impacts, including the CO_2 impacts means more activities need to be done to help verify the efficacy of the proposed solutions as shown in Table 3.

Table 3: Aircraft and engine design and their impact and challenges.

Solution	Impact	Challenges
Aircraft Design	Lower impact of NOx and contrails, 33% reduction in climate impact in propeller-powered aircraft.	Challenges in reducing aviation NOx due to commercial aviation growth and mandate to increase engine energy efficiency.
Engine design - fuel efficiency	Significant reduction in contrail EF.	Technological challenges in developing cleaner engine technologies.

4.3.1 Aircraft design

Aircraft design could play a pivotal role in mitigating the non-CO_2 impact, as evidenced by the findings of the Thijssen, Proesmans, and Vos (2022) paper on medium-range turboprop-powered aircraft and turbofan aircraft.[97] Turboprop-powered aircraft, a type of aircraft using a propulsion system where a gas turbine engine drives a propeller, are commonly used for medium-range flights, regional travel, low speed aircraft like cargo planes.[98] Turbofan aircraft, featuring a turbofan engine comprising core engine thrust and a large bypass fan, are predominantly utilised in commercial airliners designed for medium to long-range flights due to their high-speed performance and efficiency at high altitudes.[99] When evaluating the climate-optimal design of both propeller and turbofan aircrafts, there was an additional 33% reduction in climate impact observed in the propeller-powered aircraft.[100] In addition, turboprop-powered aircraft demonstrate greater propulsive efficiency than turbofan aircraft when operating at lower cruise altitude, leading to a lower impact of NOx and contrails.

[97] Thijssen, R., Proesmans, P. and Vos, R. (2022) 'Propeller Aircraft Design Optimization For Climate Impact Reduction', in. International Council of the Aeronautical Sciences, pp. 658–679. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85159699916&partnerID=40&md5=58215c2585eb6d2db69f279a7b208aab.
[98] NASA (2021) 'Turboprop Engine', Available at: https://www.grc.nasa.gov/www/k-12/airplane/aturbp.html
[99] NASA (2021) 'Turbofan Engine'. Available at: https://www.grc.nasa.gov/www/k-12/airplane/aturbf.html
[100] Thijssen, R., Proesmans, P. and Vos, R. (2022) 'Propeller Aircraft Design Optimization For Climate Impact Reduction', in. International Council of the Aeronautical Sciences, pp. 658–679. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85159699916&partnerID=40&md5=58215c2585eb6d2db69f279a7b208aab.

4.3.2 Engine design - fuel efficiency

Based on the flight track data in Japanese airspace, the research from Teoh *et al*., 2020 simulated and evaluated the contrail's impact reduction by using cleaner engine technologies such as the double annular combustor (DAC), characterised by two concentric annular combustion chambers within the engine, where the outer annulus initiates the initial combustion as the pilot stage, and the inner annulus functions as the main combustion stage facilitating fuel injection and combustion.[101] The study demonstrated a significant reduction of 68.8% [45.2, 82.1%] in the contrail EF (energy forcing – units of joules).[102]

German Aerospace Center (DLR) is developing a virtual engine, which acts as a digital representation of a real-world propulsion system and reflects every stage of an actual engine's life cycle and development. This enables continuous calculation and evaluation of the entire system. The virtual engine contains all geometric features (e.g., shape, dimensions, component layouts) and physical features (e.g., material composition, thermal properties) of a propulsion system. It is developed using computer-aided design tools and numerical simulation methods, considering key disciplines, such as aerodynamics, structural mechanics and thermodynamics.[103]

However, reducing aviation NOx through design is challenging due to the growth in commercial aviation and the mandate to increase engine energy efficiency, with potential trade-offs and co-benefits between the impacts on climate and air quality. Reductions of surface O_3 precursor emissions, such as volatile organic compounds (VOCs) and NOx that can react and contribute to the formation of surface O_3, are projected and may provide some mitigation of the aviation NOx climate impact and a net cooling. Additionally, technological advances in combustor design can help in reducing aviation NOx emissions by improving engine efficiencies.[104]

4.4 Mitigation Option: Optimised flight planning (aircraft operators) (air navigation service providers)

Some literature and trials have identified that non-CO_2 impacts including contrails from aircrafts could be avoided and prevented through relatively small deviations of flight plans, thus reducing their impact on climate change and global warming, and there are already a number of potentials suppliers (e.g. SATAVIA, FlightKeys and DLR) and adopters of such a solution (e.g. Etihad, KLM, EUROCONTROL). Through

[101] Teoh, R. et al. (2020) 'Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption', Environmental Science and Technology, 54(5), pp. 2941–2950. Available at: https://doi.org/10.1021/acs.est.9b05608.
[102] Teoh, R. et al. (2020) 'Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption', Environmental Science and Technology, 54(5), pp. 2941–2950. Available at: https://doi.org/10.1021/acs.est.9b05608.
[103] German Aerospace Center (DLR). (2022). Compute Before Flight. [Online] ,Available at: https://www.dlr.de/en/media/publications/magazines/2022_dlrmagazine-170-compute-before-flight/
[104] International Civil Aviation Organization (ICAO). (2022). ICAO Environmental Report 2022. [Online] Available at: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO%20ENV%20Report%202022%20F4.pdf

numerical weather prediction modelling and contrail modelling, this type of solution would only require light-touch software solutions with low operational impact and would have a low associated fuel burn penalty. However, this is significantly dependent on developing clear metrics with acceptable, quantifiable uncertainties in weather modelling and contrail climate impact quantification. The challenges include:

- Modelling complex atmospheric dynamics: predicting the specific location of ice supersaturated regions (ISSR) in the atmosphere in advance is challenging – see section 4.1 for more details.
- The need for enhanced air traffic management: if many aircraft are avoiding an ISSR this may put a strain on Air Traffic Management.
- Potential fuel burn and CO_2 penalties incurred due to re-routing.

4.4.1 Climate-restricted airspaces (CRAs)

Given that inflight trajectories optimisation strategies may not able to address the technical challenges in the near future, Niklaß et al (2019) introduced an interim mitigation strategy, Climate-Restricted Airspaces (CRA). These are akin to military exclusion zones but are determined using on 3-D climate change functions to assess the environmental impact of aircraft emission at specific locations. In areas where the climate cost exceeds a certain threshold, the access is restricted in a given month, while other regions remain open for air traffic. A initial analysis assessed the cost-benefit potential of this strategy on Helsinki (EFHK)-Miami (KMIA) route, which demonstrated considerable opportunities to reduce the aviation-related climate warming without incurring additional operational expenses. This can be achieved either through climate-optimized routes, resulting in a 12% reduction, or by avoiding CRA, leading to an 8.7% decrease, provided that 28.8% of the total airspace is restricted. However, such strict airspace limits may strain capacity of the air transportation system. Therefore, rerouting around CRA should focus on the most harmful trajectories to enable eco-friendly growth of air traffic. [105]

Aircraft-Induced-Clouds (AIC) Abatement Program (AAP): It is essential to establish an AAP when the industry opts for avoiding flights fly over the Ice Super Saturated Regions (ISSR) to mitigate AIC (i.e., contrails). Accordingly, Sherry, Rose and Thompson (2021) introduce a system design aimed at creating a collaborative Airline and Air Traffic Control system to address AIC by regulating the Cruise Flight Level assignment in relation to ISSR presence. The proposed AAP is expected to function similarly to existing Traffic Flow Management Programs, but an additional effort will be required to detail its protocols and rules.[106]

[105] Niklaß, M., Lührs, B., Grewe, V., Dahlmann, K., Luchkova, T., Linke, F., & Gollnick, V. (2019). Potential to reduce the climate impact of aviation by climate restricted airspaces. Transport Policy, 83, 102–110. https://doi.org/10.1016/j.tranpol.2016.12.010
[106] Sherry, L., Rose, A., & Thompson, T. (2021). Design of an aircraft induced cloud (AIC) abatement program (AAP) for global warming mitigation. 2021-April. https://doi.org/10.1109/ICNS52807.2021.9441627

4.4.2 Climate-charged airspaces (CCAs)

A policy concept called climate-charged airspaces (CCAs) aims to encourage airlines to choose climate-friendly routes (those where non-CO_2 impacts are reduced). This concept implements a climate charge on airlines for operating in regions highly susceptible to climate change. By doing so, airlines have an incentive to avoid these areas, which can lead to both a reduction in climate impact and operating costs. The findings from trajectory simulation on a specific North-Atlantic route network indicated that CCAs could averagely achieve over 90% of the potential reduction in the climate impact compared to climate-optimised trajectories (theoretical maximum, benchmark).[107]

4.5 Mitigation Option: In-flight avoidance

Avoiding flying through areas with very cold and humid conditions (ISSRs), is a key lever to reduce contrails. Changing flight paths to fly at a lower altitude, or performing small diversions, can avoid contrail formation. Breakthrough Energy, Google, MIT (Massachusetts Institute of Technology) and Imperial College are currently potential suppliers of tools to achieve this by making in-flight deviations. An advantage of this solution is that it would leverage real-time observational imagery through satellite observation and artificial intelligence. However, this solution only applies when contrails have already formed in a region. The challenges include:

- A need for in-flight changes to flight trajectory – this would increase the workload of air traffic controllers.[108]
- There is less time for the trajectory to be optimised.[109]

4.5.1 Optimisation modules for aircraft trajectory optimisation

One study suggested an optimisation module for aircraft trajectory, with the aim of minimising the climate impact of both aircraft emissions and contrails. The proposed module integrates aircraft fuel burn and emission, contrail formation, and a simplified climate response model with a national-level airspace simulation and has been used to generate alternate aircraft trajectories for 12 flights between city pairs to study their energy efficiency and environmental impact. The study indicates that contrail reduction can be achieved through changes in both route and altitude, and this approach is more energy efficient compared to using only one of these factors. For the simulation with the wind-optimal routes as the baseline, the optimal lateral contrail reducing (LCR) trajectories can reduce the contrail formation time from 5885 to 2995 minutes but require an extra 90,000 kg of fuel. In contrast, three-dimensional contrail-reducing aircraft trajectories can initially cut down the contrail formation time

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[107] Niklaß, M. *et al.* (2021) 'Concept of climate-charged airspaces: a potential policy instrument for internalizing aviation's climate impact of non-CO2 effects', *Climate Policy*, 21(8), pp. 1066–1085. Available at: https://doi.org/10.1080/14693062.2021.1950602.

[108] Molloy, J., Teoh, R., Harty, S., Koudis, G., Schumann, U., Poll, I. and Stettler, M.E., 2022. Design principles for a contrail-minimizing trial in the north atlantic. *Aerospace*, *9*(7), p.375.

[109] Molloy, J., Teoh, R., Harty, S., Koudis, G., Schumann, U., Poll, I. and Stettler, M.E., 2022. Design principles for a contrail-minimizing trial in the north atlantic. *Aerospace*, *9*(7), p.375.

to 2510 minutes while saving 21,000 kg of fuel. The study also emphasises the consideration of the value associated with climate-reducing trajectories, which varies among aviation stakeholders, and explores that a hypothetical tax on contrail production would influence a stakeholder's willingness to redefine their optimal cruise trajectory.[110]

A study conducted in Japan simulated and evaluated the impact of contrail reduction strategies on individual flights. The findings revealed that a small-scale strategy of diverting flights with the largest contrail EF could significantly reduce the contrail EF. This strategy involves selectively diverting 1.7% of the fleet, which can lead to a substantial reduction in contrail EF by 59.3% [52.4, 65.6%], with minimal increases (0.014% [0.010, 0.017%]) in fuel consumption and CO_2 emissions.[111]

Grewe et al. (2014) employed 5-D climate cost functions, considering emission location (3D), time and type, to optimise flight routes and analyse trans-Atlantic air traffic during a particular winter day. They observed a substantial decrease in the impact of air traffic on the climate warming, with reductions of up to 60% for westbound flights and around 25% for eastbound flights. However, achieving the highest reduction in climate impact leads to a higher fuel penalty due to extended flight distance and reduced flight altitudes, resulting in a corresponding 10% -15% increase in economic costs. Nonetheless, minor adjustments to air traffic routings and flight levels can incur minimal cost penalty, less than 0.5%, but still decreasing the climate impact by up to 25%.[112]

4.5.2 Path-planning approach/trade-off between contrail mitigation and fuel consumption

Choosing a climate-optimal trajectory often entails increased fuel consumption, necessitating a trade-off between contrail mitigation and fuel efficiency. The subsequent research introduces several innovative approaches, demonstrating that even a slight increase in fuel consumption can yield a substantial reduction in climate impact.

- **Mixed-integer linear programming**: This approach is employed within a receding horizon framework to generate aircraft trajectories aimed at addressing persistent contrail formation while simultaneously minimising fuel consumption. In a single-flight scenario, the strategy results in a 48% reduction in persistent contrails, accompanied by a marginal 0.5% increment in fuel usage. An absolute contrail avoidance results in a 6.2% increase in fuel consumption. Analysing this route over 20-day period of atmospheric data reveals that a mere 0.48% increase

[110] Sridhar, B. et al. (2013) 'Energy efficient trajectory designs for minimizing climate impact of aircraft on various timescales', in. AIAA Modeling and Simulation Technologies (MST) Conference. Available at: https://aviationsystems.arc.nasa.gov/publications/2013/AIAA-2013-4600.pdf
[111] Teoh, R. et al. (2020) 'Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption', Environmental Science and Technology, 54(5), pp. 2941–2950. Available at: https://doi.org/10.1021/acs.est.9b05608.
[112] Grewe, V., Champougny, T., Matthes, S., Frömming, C., Brinkop, S., Søvde, O. A., Irvine, E. A., & Halscheidt, L. (2014). Reduction of the air traffic's contribution to climate change: A REACT4C case study. Atmospheric Environment, 94, 616–625. https://doi.org/10.1016/j.atmosenv.2014.05.059

in fuel consumption can lead to a potential avoidance of 58% of persistent contrails.[113]

- **Algorithmic climate change functions**: This methodology uses algorithmic climate change functions in trajectory optimisation. It was applied on around 13,000 intra-European flights during a day with significant contrail formation. Results show a 50% reduction in climate impact with just a 0.75% increase in fuel burn. Higher reductions up to 76% are possible but require much higher fuel penalties of 12.8%. However, these solutions are less efficient for climate impact mitigation.[114]
- **Weather data-driven flight path planning**: This approach suggests that flights can be re-routed from sufficiently cold and humid atmospheres to mitigate the level of contrail production in particular regions during the flight planning stage. A weather data-driven flight path planning is proposed, utilising historical data to generate the spatial meteorological condition and formulates it as uncertain factors to devise a robust solution. Airlines can set their allowances for flight level adjustments, adhere to pre-determined constrained flight levels, and enhance robustness against the maximum tolerance level of uncertain contrail length along a flight path. This strategy seeks to minimise overall costs by reducing total contrail length while minimising additional fuel consumption expenses.[115]
- **Flight trajectory planning and optimisation model:** Xue et al. (2020) presented a flight trajectory planning and optimisation model designed to reduce various performance metrics, consisting of total flight time, fuel consumption and environmental impact in relation to contrails. [116] The research calculated the thickness of Persistent Contrail Formation Areas (PCFA) using 2014 radio soundings data from Nanjing (China) and computed the spatial distribution of PCFA along the flight path, based on meteorological conditions (including pressure, temperature, relative humidity, etc.) between seven sounding observation stations in China. The optimisation results showed that an optimal selection of altitude and true airspeed can achieve significant reduction in contrail length, establishing a valuable benchmark for flight route planning, incorporating environmental considerations. However, several concerns were also raised about the frequent flight altitude changes, such as potential air traffic conflicts, increased workload for Air Traffic Controllers and pilots and passenger discomfort.[117]Seeking climate-optimised flight trajectories requires dedicated

[113] Campbell, S.E., Bragg, M.B. and Neogi, N.A. (2013) 'Fuel-optimal trajectory generation for persistent contrail mitigation', Journal of Guidance, Control, and Dynamics, 36(6), pp. 1741–1750. Available at: https://doi.org/10.2514/1.55969.
[114] Lührs, B. et al. (2021) 'Climate impact mitigation potential of European air traffic in a weather situation with strong contrail formation', Aerospace, 8(2), pp. 1–15. Available at: https://doi.org/10.3390/aerospace8020050.
[115] NG, K.K.H. (2023) 'Emission-aware adjustable robust flight path planning with respect to fuel and contrail cost', Transportmetrica B, 11(1), pp. 24–68. Available at: https://doi.org/10.1080/21680566.2022.2036651.
[116] Xue, D., Ng, K. K. H., & Hsu, L.-T. (2020). Multi-objective flight altitude decision considering contrails, fuel consumption and flight time. Sustainability (Switzerland), 12(15). https://doi.org/10.3390/SU12156253
[117] Xue, D., Ng, K. K. H., & Hsu, L.-T. (2020). Multi-objective flight altitude decision considering contrails, fuel consumption and flight time. Sustainability (Switzerland), 12(15). https://doi.org/10.3390/SU12156253

meteorological services to identify regions where emissions significantly affect the climate.

Algorithmic Climate Change Functions (aCCFs) offer prototypes for mathematical formulations to assess the temporal and spatial climate effects of aviation emissions. Here list several types of aCCFs explored in the recent research. These include**:**

- **CLIMaCCF:** This is an open-source Python library that offers detailed spatial and temporal data regarding the impact of aviation on climate, specifically focusing on future near-surface temperature change. It's able to compute both the individual aCCFs (for water vapor, NOx-induced ozone production, methane depletion, and contrail cirrus) and the combined non-CO_2 aCCFs, consolidating all these individual contributions[118]
- **Submodel ACCF 1.0 of the chemistry–climate model EMAC:** These are algorithmic Climate Change Functions that represent the basis for estimating the climate impact of aviation emissions. The sub-model ACCF 1.0 of the chemistry–climate model EMAC was employed to assess the climate impact of aviation emissions within the flight corridor of the Northern Hemisphere.[119]
- **Multi-dimensional aCCFs** These are algorithmic climate change functions designed for quantifying the climate impact of emissions, which utilise meteorological parameters sourced from weather forecast data. Integrated into the cost functional of a trajectory planning algorithm, they can enable the estimation of climate-optimised aircraft trajectories that balances the reduction of climate impact against potential increases in costs.[120]

4.6 Mitigation Option: Lower flight

Reduction in maximum flight altitude by 2,000 meters has been reported to have the ability to reduce the climate impact of aviation sector by up to 70% [121]. However, altitude deviations should be considered on a flight-by-flight basis so as not to inadvertently increase contrail climate forcing and to consider the fuel consumption trade-off. ISSR formation occurs differently on any given day. Accordingly, various strategies have been proposed and investigated in the following paragraphs, encompassing vertical diversion tactics, alterations in flight levels, and grid shifting scheme:

[118] Dietmüller, S. et al. (2023) 'A Python library for computing individual and merged non-CO2 algorithmic climate change functions: CLIMaCCF V1.0', Geoscientific Model Development, 16(15), pp. 4405–4425. Available at: https://doi.org/10.5194/gmd-16-4405-2023.
[119] Yin, F. et al. (2023) 'Predicting the climate impact of aviation for en-route emissions: the algorithmic climate change function submodel ACCF 1.0 of EMAC 2.53', Geoscientific Model Development, 16(11), pp. 3313–3334. Available at: https://doi.org/10.5194/gmd-16-3313-2023.
[120] Meuser, M.M. et al. (2022) 'Mitigation Of Aviation's Climate Impact Through Robust Climate Optimized Trajectories In Intra-European Airspace', in. International Council of the Aeronautical Sciences, pp. 6553–6567. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85159679765&partnerID=40&md5=8862b151defbbf49f9beac4583577c3e.
[121] German Aerospace Center (DLR). (2023, March). Long-haul flights: Small changes with a big climate impact. [Online] Available at: https://www.dlr.de/en/latest/news/2023/03/long-haul-flights-small-changes-with-a-big-climate-impact

- **Vertical diversion strategies**: The Teoh, Schumann and Stettler, 2020 study assesses various vertical flight diversion strategies aimed at reducing contrail climate forcing and evaluates their impacts on air traffic management (ATM).[122] The findings indicate that one strategy diverts 15.3% of flights to avoid long-lived warming contrails, reducing the contrail energy forcing (EFcontrail) by 105% [91.8, 125%] with a 0.70% [0.66, 0.73%] fuel increase. Another strategy, minimising total energy forcing (EFtotal) by considering both contrails and CO_2 emissions and diverting 20.1% of flights, achieves a similar reduction in EFcontrail while also decreasing total fuel consumption by 0.40% [0.31, 0.47%][123]
- **Change in flight level**: The tropopause height influences not only contrail occurrence but also the preferred flight level, as airlines tend to avoid flying directly in the tropopause. Since the majority of air traffic occurs at the highest flight levels, close to the maximal flight level, any prospective operational adjustments in air traffic control to avoid contrails (ice supersaturated air mass flight levels) are anticipated to lead to increased fuel consumption due to the need to lower aircraft flight levels, however the actual impact could potentially be negligible.[124] The most significant result of the Lán and Hospodka, 2022 paper and the most important suggestion would be not to focus on all flights, but to focus on aircraft with potential for producing persistent contrails only.[125]
- **Grid shifting scheme**: The Wei *et al*., 2013 paper introduces a contrail reduction scheme that uses the defined Monitor Alert Parameter value as the sector capacity constraint.[126] This approach differs from the conventional method of adjusting cruise altitude across vertical grids for all aircraft within a centre. Instead, it selectively shifts specific aircraft out of grids in regions susceptible to persistent contrails. This grid shifting scheme offers a finer resolution compared to the level shifting method, leading to an enhanced contrail mitigation and decreased fuel consumptions. Additionally, the planning interval is shortened from one hour to one-minute, leading to more precise temporal resolution in solution results.[127]

4.7 Mitigation Option: Daytime flight only

Some researchers suggested that limiting flight operations to daytime-only could serve as a potential mitigation measure considering that night-time flights

[122] Teoh, R., Schumann, U. and Stettler, M.E.J. (2020) 'Beyond contrail avoidance: Efficacy of flight altitude changes to minimise contrail', Aerospace, 7(9). Available at: https://doi.org/10.3390/AEROSPACE7090121.
[123] Teoh, R., Schumann, U. and Stettler, M.E.J. (2020) 'Beyond contrail avoidance: Efficacy of flight altitude changes to minimise contrail', Aerospace, 7(9). Available at: https://doi.org/10.3390/AEROSPACE7090121.
[124] Lán, S. and Hospodka, J. (2022) 'Contrail Lifetime in Context of Used Flight Levels', Sustainability (Switzerland), 14(23). Available at: https://doi.org/10.3390/su142315877.
[125] Lán, S. and Hospodka, J. (2022) 'Contrail Lifetime in Context of Used Flight Levels', Sustainability (Switzerland), 14(23). Available at: https://doi.org/10.3390/su142315877.
[126] Wei, P. et al. (2013) 'Vertical grid shifting approach to the development of contrail reduction strategies with sector capacity constraints', in. American Institute of Aeronautics and Astronautics Inc. Available at: https://doi.org/10.2514/6.2013-5177.
[127] Wei, P. et al. (2013) 'Vertical grid shifting approach to the development of contrail reduction strategies with sector capacity constraints', in. American Institute of Aeronautics and Astronautics Inc. Available at: https://doi.org/10.2514/6.2013-5177.

significantly contribute to contrail forcing. A 2006 study revealed that night-time flights contribute to 60%-80% of contrail forcing despite accounting for only a quarter of all flights. This is because, while contrails trap heat during both day and night, this effect is partially counteracted during the day by a cooling effect as they reflect sunlight back into space.[128] There are a number of operational, capacity (including freight traffic) and social constraints as well as time zone differences (considering long haul flights) that are limiting operating daytime flights only.

- **Next-generation Multi-Objective Trajectory Optimisation (MOTO):** Next-generation Multi-Objective Trajectory Optimisation (MOTO) enables the generation of optimal flight trajectories considering multiple objectives, with dynamic weights adjusted based on the flight phase. Lim et al., (2017) conducted a case study focusing on a direct flight of a Boeing B777-200 from Paris to Beijing. A MOTO algorithm was employed to optimise the trajectories aimed at minimising the radiative impact of contrails and CO_2 emissions, as well as minimizing travel time and fuel consumption. The study effectively showcased the practicality of this algorithm in offering both strategic and tactical capabilities for optimising trajectories. Furthermore, the study observed that the optimizer devised trajectories that avoid regions prone to persistent contrails at night and sought out such regions during the day. This was due to the variation in contrail-induced radiative forcing (RF) throughout the day, with positive RF at night and negative RF during the day. This finding highlights the importance of considering the temporal variation of contrail RF when designing optimal, minimal-RF trajectories.[129]

4.8 Mitigation Option: Formation flights

Besides the fuel-saving benefits attained from formation flights, in airspace conditions prone to persistent contrail formation, formation flight can mitigate the net contrail effect. This occurs as multiple persistent contrails in the same region compete for available water vapour, leading to mutually inhibit of growth. Consequently, the combined warming effect is reduced compared to individual contrail generation. This effect has been extensively investigated by Unterstrasser (2020).[130] [131]

German Aerospace Center (DLR) is analysing the possibility to adopt the V-shaped formation used by migratory birds in long haul flights through Formation Flight Impact

[128] Carbon Brief (2017) 'The challenge of tackling aviation's non-CO2 emissions'. Available at: https://www.carbonbrief.org/explainer-challenge-tackling-aviations-non-co2-emissions/
[129] Lim, Y., Gardi, A., & Sabatini, R. (2017). Optimal Aircraft Trajectories to Minimize the Radiative Impact of Contrails and CO2 (H. Chowdhury, F. Alam, & R. Jazar, Eds.; Vol. 110, pp. 446–452). Elsevier Ltd. https://doi.org/10.1016/j.egypro.2017.03.167
[130] Unterstrasser, S. (2020). The contrail mitigation potential of aircraft formation flight derived from high-resolution simulations. Aerospace, 7(12), 1–22. https://doi.org/10.3390/aerospace7120170
[131] Khan, A.H. et al. (2023) 'Off-setting climate change through formation flying of aircraft, a feasibility study reliant on high fidelity gas-phase chemical kinetic data', International Journal of Chemical Kinetics, 55(7), pp. 402–412. Available at: https://doi.org/10.1002/kin.21644.

on Climate (FORMIC) project. Studies conducted by DLR showed that it can reduce the fuel consumption by 5% and reduce the climate impact by 25%.[132]

4.9 Stakeholder workshop insights

There was consensus at the workshop that, while there's no perfect solution, leveraging existing technologies remains crucial in earnestly reducing emissions and their adverse effects. Discussions revealed differences of opinion about the materiality of extra fuel burn, urging a shift towards environmentally optimised flight planning rather than purely economic considerations. Discussion also centred almost solely on contrails as opposed to other non-CO_2 impacts.

The mitigation approach focused on managing contrails rather than avoiding them, with specific flight types identified as significant contributors to warming. Collaborative learning across industries, including insights from military predictive capabilities, was deemed crucial for more effective mitigation strategies.

Resistance to action on contrail management usually centres around a) “scientific uncertainty” and b) incurring a known CO_2 and economic cost from a ‘fuel burn penalty’ (e.g., from adjusting altitude to avoid contrail formation) and c) no driver to change, due to there being no penalty for non-CO_2 impacts. Adding a penalty for non-CO_2 impacts at this time is challenging due to the difficulties in predicting contrails, uncertainties around their impacts and the metrics used to measure their impact.

Given the nature of science, there is rarely absolute consensus or certainty. However, from the literature review conducted there is believed to be a reasonable confidence and consensus around the case for targeted interventions at this point. Real world trials show that fuel burn penalties can be immaterial (e.g., significantly smaller than the ‘fuel burn penalty’ of waiting on tarmac for the next available slot, or of flying routes that avoid more expensive airspace, and crucially significantly smaller than the avoided non-CO_2 climate impact of contrail formation on night-time flights).

The key is therefore being sure on the small % flights contributing to most of the net warming, for which an intervention in flight plan is immaterial in terms of fuel burn. The current fuel argument is based on an economic optimum for flight planning, not environmental, and may be inadequate to maximising climate benefits through a whole-systems approach that considers wider positive outcomes.

4.10 Conclusion

The aviation industry faces the challenge of addressing non-CO_2 climate impacts, particularly those related to contrail formation and emissions of NOx and nvPM. Various mitigation options have been explored in this chapter, each with its own

[132] German Aerospace Center (DLR). (2021, February 23). Flying in Formation to Reduce Climate Impact. [Online] Available at: https://www.dlr.de/en/latest/news/2021/02/20210623_flying-in-formation-to-reduce-climate-impact

strengths, weaknesses, and dependencies. These options include the use of alternative fuels like SAF, hydrogen, and ammonia, improvements in aircraft and engine design, optimised flight planning, in-flight avoidance strategies, lower flight altitudes, daytime flights only, and formation flights.

Each solution varies in its technological readiness, impact on climate and emissions, and operational feasibility. The effectiveness of these solutions often depends on factors like fuel availability, technological advancements, regulatory environments, and the ability to integrate changes into existing aviation systems. Collaborative efforts across the industry and continued research are essential to develop and implement these solutions effectively.

Table 4: Summary table of mitigation options.

Mitigation	Positive Impacts	Negative Impacts/Challenges
Alternative fuels (SAF, hydrogen, ammonia)	- SAF: reduces contrail RF, lowers emissions of non-volatile particles, cuts air pollution. - Hydrogen: potential reduction in NOx emissions. - Ammonia: potential for NOx reduction, minimises contrail formation.	- SAF: limited supply, high cost, and if used on only the most impactful flights, practical separate storage and distribution. - Hydrogen: potential increase in contrails due to higher water vapour emissions. - Ammonia: requires technological advancements, safety measures for toxicity, implementation challenges in existing aircraft.
Aircraft and engine design	- Lower NOx and contrail impact. - Improved fuel efficiency. - Potential 33% reduction in climate impact with propeller-powered aircraft.	- Technological challenges in cleaner engine technologies. - Growth in commercial aviation increases difficulty in reducing NOx. - Trade-offs between efficiency and emission reduction.
Optimised flight planning	- Reduced contrail formation. - Lower overall climate impact. - Can be tailored for specific flight paths and conditions.	- Complex atmospheric dynamics make prediction difficult. - Strain on air traffic management. - Potential fuel burn and CO_2 penalties due to rerouting.
In-flight avoidance	- Avoidance of areas conducive to contrail formation. - Real-time adaptability using ai and satellite imagery.	- Increased workload for air traffic controllers. - Less time for route optimisation. - Operational complexity and safety considerations.
Lower flight altitude	- Substantial reduction in aviation's climate impact. - Can be a direct and effective approach.	- Increased fuel consumption at lower altitudes. - Potential air traffic management challenges. - May not be feasible for all flight types.
Daytime flight only	- Reduced contrail forcing at night (contrails trap more heat at night than during the day). - Can be effective for specific routes and seasons.	- Operational and capacity constraints, especially for long-haul flights. - Time zone differences complicate scheduling - May not be feasible for freight traffic.
Formation flights	- Fuel savings from aerodynamic benefits. - Reduced net contrail effect in formation. - Explores innovative approaches in flight dynamics.	- Operational complexity in coordinating formation flights. - Safety concerns with close proximity flying. - Applicability primarily in specific flight conditions.

Overall, while there is no single "silver bullet" solution, a combination of these mitigation strategies, tailored to specific flight types and conditions, appears to be the most promising approach for managing aviation's non-CO_2 climate impact. The key lies in precise and collaborative efforts across the industry, leveraging existing technologies and continuously updating with new findings. The extensive research on aviation's non-CO_2 impacts reveals a complex and significant role in climate change, highlighting the sector's broader environmental footprint beyond CO_2 emissions. Contrail cirrus and NOx emissions emerge as substantial contributors to global warming, rivalling or even exceeding the impact of CO_2 in certain research. However, the inherent uncertainties in quantifying these effects pose a challenge, necessitating a nuanced approach to emission measurement and management.

Optimised flight planning and in-flight avoidance strategies also offer tangible benefits in reducing contrail formation, albeit requiring sophisticated weather modelling and operational adaptations. Alternative fuels like SAF and hydrogen, along with advancements in aircraft and engine design, present promising avenues for mitigation. Yet, like flight planning and in-flight avoidance strategies, these solutions are not without their own complexities and potential trade-offs, especially concerning the balance between CO_2 and non-CO_2 impacts.

The literature review emphasises the need for greater precision in measuring and understanding the full spectrum of aviation's climate impacts. This includes a call for refined climate metrics (Section 5) and counterfactual analyses to better grasp the nuances of aviation emissions.

The insights from the stakeholder workshop shed light on the industry's consensus regarding the imperative of leveraging existing technologies to reduce non-CO_2 emissions. They emphasise the importance of prioritising environmental optimised flight planning in addition to economic considerations. Although resistance to contrail management typically revolves scientific uncertainty, extra fuel burn penalty and the absence of a driving force for change, the real-world trials suggest that targeted interventions can yield significant climate benefits with minimal fuel burn penalties. Moving forward, ongoing research, collaborative learning and a holistic approach will be essential in maximising climate benefits within the aviation sector.

Next steps in this space could include intensifying research efforts to address the gaps in understanding the full climatic impact of non-CO_2, particularly contrail cirrus and NOx. This involves conducting targeted studies, collecting, and analysing data, and developing models to better quantify the effects of these emissions. There is also a need to develop and refine climate metrics that can accurately quantify the impact of both CO_2 and non-CO_2. This includes developing metrics that can capture the radiative forcing and other climate effects of non-CO_2, as well as integrating these metrics with existing CO_2 metrics.

In summary, a multifaceted strategy encompassing research, technological innovation, operational adjustments, stakeholder collaboration, and public engagement is essential to effectively mitigate the aviation sector's impact on climate change.

5 Evaluation of the existing methodologies and metrics to measure the non-CO_2 impacts of aviation

5.1 Introduction

Climate metrics are crucial for comparing the impact of different emissions and forcings in aviation. However, their application can be complex due to the varying effects of short-lived and long-lived forcings. This chapter explores the nuances of climate metrics and their implications for decision-making.

Each climate metric captures a specific aspect of an activity's impact. Converting non-CO_2 forcings into CO_2-equivalent emissions using different metrics results in varying values. This means that a metric-defined CO_2-equivalence is not unique, and the choice of metric will affect the valuation of the non-CO_2 forcing. Short-lived effects (e.g., contrails, aerosol) will be strongly dependent on the time horizon chosen as they have the strongest impact in the near-term.

Depending on the question, a different metric or time horizon will be needed to approximate the desired information. For example, if limiting global warming at a particular time is the goal, a metric that reflects the effect on temperature at that time is required. A different time horizon would be needed for 2070 or 2100. A different metric would be needed if the impact over a time period (e.g., 2030 to 2050) were needed instead of a time snapshot. This highlights the need for multiple metrics in aviation decision-making, as no single metric can address all needs.

It is recommended to separate short-lived pollutant emissions targets from long-lived emissions for clarity, as the effects last for different time periods. This allows for a more accurate assessment of the impact of each type of emission.

Stakeholders and scientists should have a structured process to find a common understanding of what metrics are required for aviation and to explore what metrics could fulfil the range of stakeholder needs. This process should be open and transparent so that the logic of identifying the suite of metrics recommended can be understood widely, as this is likely to be a precursor to wide usage.

By employing appropriate climate metrics and considering their strengths and limitations, policymakers and stakeholders can make informed decisions to mitigate climate change effectively, incorporating lessons learned from real-world planning and practice.

Addressing the challenges of short-lived forcings

Climate metrics were developed to compare the climate impact of greenhouse gases on global and multi-year scales. However, some compounds like contrails have short residence times, and their impact varies depending on the time period considered.

This poses challenges in comparing the climate impact of contrail-cirrus (short-lived, regional) with CO_2 (long-lived, global). Uncertainties in estimating non-CO_2 impacts and the effectiveness of avoidance measures add to the complexity. Analyses show that a small number of flights contribute significantly to contrail-cirrus forcing, suggesting targeted mitigation actions. The choice of climate metric can influence decisions and crediting mechanisms for individual flights. Improved metrics and understanding of contrail-cirrus efficacy are needed to incentivise effective avoidance measures. Contrails are less efficient than CO_2 in producing global warming, highlighting the need for tailored approaches to address non-CO_2 impacts in aviation.

Formulating a net-zero climate goal

The formulation of a net-zero climate goal for aviation requires a solid scientific understanding to avoid unintended consequences. Using a simple CO_2 equivalent (CO_2-equivalent) metric can lead to adverse effects, as such metrics cannot provide equivalence for short- and long-lived forcings at more than one time scale. Different commonly used metrics result in varying weightings for non-CO_2 impacts, affecting allowable emissions and temperature outcomes. To address this, setting an aggregated CO_2-equivalent target should be avoided. Instead, limits on emissions for each gas and ERF from contrails could be established; or long- and short-lived forcings targeted separately. Alternatively, 'warming-equivalent' or 'flow-based' metrics, like GWP* (a global warming potential which takes short-lived gas removal from the atmosphere into consideration), can capture short-lived forcing effects more accurately. GWP* considers present-day trends and requires proper application based on the question asked. Metrics should inform specific problems, such as reducing non-CO_2 impacts to meet government targets.

5.2 Summary of internationally identified climate metrics for measuring aviation's non-CO_2 impacts

What are climate metrics and what are they used for? A climate metric, as referred to here, is sometimes also called a climate emission metric, or emission metric, or a greenhouse gas emissions metric. The most commonly used metrics when describing non-CO_2 impacts are[133]:[134]

- **Radiative forcing (RF):** RF of a greenhouse gas (GHG) is the energy imbalance caused by the released gas at a given time. Unit: W m^{-2}. RF of aviation emissions results from adding the RF of all the gases and contrail effects in the aviation emissions basket.

[133] RF and ERF are the basis for a number of other metrics, whilst AGTP is the foundation of GTP and AGWP the foundation of GWP. As they are updated into other metrics, they are not referred to further in this section
[134] Roland Berger. (n.d.). Time to Measure Up. [Online] Available at: https://www.rolandberger.com/en/Insights/Publications/Time-to-measure-up.html

- **Effective Radiative Forcing (ERF):** ERF of GHG is an amendment of the pure RF, allowing for atmospheric adjustments. ERF is more closely linked to the long-term temperature change caused by the forcing than RF is. Unit: W m^{-2}. ERF of aviation emissions results from adding the ERF of all the gases and contrail effects in the aviation basket
- **Absolute Global Warming Potential (AGWP):** AGWP of GHG is the RF caused by a 1kg emission of the gas into the atmosphere, integrated over a time period (e.g., 100 years). Units: W m^{-2} year kg^{-1}.
- **Global Warming Potential (GWP):** GWP of GHG is the RF caused by a 1kg emission of the gas into the atmosphere integrated over a time period (e.g., 100 years), normalised to the same for CO_2 (i.e. AGWP of the forcing agent divided by AGWP of CO_2) Unit: dimensionless. This is a measure of the total energy added to the system averaged over the specified time period following the emission; GWP of aviation emissions results from adding the GWP of all the gases and contrail effects in the aviation emissions basket.
- **Global Warming Potential-star (GWP*):** GWP* is a modified use of GWP which represents short-lived forcings using two terms to capture the short-term and the much weaker long-term impacts from such forcings. CO_2-e emissions calculated using GWP100 are multiplied by 0.28 and added to the net CO_2-e emissions increase or decrease over the previous 20 years multiplied by 4.24. Unit: dimensionless.
- **Absolute Global Temperature-change Potential (AGTP):** It represents the global temperature increase caused by aviation at a specified time horizon. Unit: K per X where X is the choice of functional unit, e.g. km flown or km^2 of contrail area.
- **Global Temperature-change Potential (GTP):** It represents the global temperature increase caused by aviation at a specified time horizon, normalised to CO_2. Unit: dimensionless.

The IPCC definition of a metric (see Box 1) refers specifically to GHGs, but many metrics can be applied for other forcings (e.g., secondary pollutants or contrails) by formulating the metric in terms of radiative forcing instead of the mass emitted.

In the aviation literature, the key metrics listed in Table 5 are the most widely used, and often applied in a bespoke manner to aviation. Examples include normalising AGWP by distance flown, or incorporating regional sensitivity as impacts of NOx emissions vary geographically.[135] [136] [137] [138] [139] [140] Some authors have developed aviation-specific metrics, which are often based upon RF or ERF, e.g. as described in section 4.2.1, Contrail Energy Forcing (EFContrail) which is the radiative forcing from the contrail, integrated across the area of the contrail and a specified duration. Table 5 distinguishes absolute and relative metrics. Absolute metrics denote the impact on climate of the action in question in an absolute sense. Relative metrics denote the impact relative to CO_2 and are thus used to convert non-CO_2 forcings into CO_2-equivalent.

Table 5: Classification of the identified metrics. Relative metrics can be used to convert non-CO_2 emissions or forcings into CO_2-equivalent emissions.

Absolute	Relative to CO_2
AGWP	GWP
AGTP	GTP
	GWP*

As part of this review, existing and possible metrics and methods were analysed in an attempt to define a single metric to support future interventions to reduce non-CO_2 impacts. We present a matrix of possible metrics in Table 6. This approach is in line with the metrics literature and the IPCC. To provide essential context to frame the evaluation of climate metrics, we have included Box 1, which summarises key points made by the IPCC in its most recent assessment cycle. Of particular relevance here is the IPCC recommendation to consider multiple metrics in making decisions to meet the goals of society.

Box 1: The IPCC view on climate emissions metrics. This text summarises their key insights on how metrics can be used for policy purposes, in accordance with climate science

— The Intergovernmental Panel on Climate Change (IPCC) provides a consensus on the current state of understanding of climate emissions metrics, and the material contained in this box is directly from its Sixth Assessment Report. The IPCC definition refers specifically to GHGs, but many metrics can be applied for other forcings (e.g., secondary pollutants or contrails) by formulating the metric in terms of radiative forcing instead of the mass emitted.

[135] Krammer, P., Dray, L. and Köhler, M.O. (2013) 'Climate-neutrality versus carbon-neutrality for aviation biofuel policy', Transportation Research Part D: Transport and Environment, 23, pp. 64–72. Available at: https://doi.org/https://doi.org/10.1016/j.trd.2013.03.013.
[136] Köhler, M.O. et al. (2013) 'Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics', Atmospheric Environment, 64, pp. 1–9. Available at: https://doi.org/10.1016/j.atmosenv.2012.09.013.
[137] Lund, M.T. et al. (2017) 'Emission metrics for quantifying regional climate impacts of aviation', Earth System Dynamics, 8(3), pp. 547–563. Available at: https://doi.org/10.5194/esd-8-547-2017.
[138] Tasca, A.L. et al. (2021) 'Innovative box-wing aircraft: Emissions and climate change', Sustainability (Switzerland), 13(6). Available at: https://doi.org/10.3390/su13063282.
[139] Skowron, A., Lee, D.S. and De León, R.R. (2015) 'Variation of radiative forcings and global warming potentials from regional aviation NOx emissions', Atmospheric Environment, 104, pp. 69–78. Available at: https://doi.org/10.1016/j.atmosenv.2014.12.043.
[140] Lee, D.S. et al. (2021) 'The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018', Atmospheric Environment, 244. Available at: https://doi.org/10.1016/j.atmosenv.2020.117834.

— The IPCC Glossary (citation) states that:

— **"Greenhouse gas emission metric:** A simplified relationship used to quantify the effect of emitting a unit mass of a given greenhouse gas on a specified key measure of climate change. A relative GHG emission metric expresses the effect from one gas relative to the effect of emitting a unit mass of a reference GHG on the same measure of climate change. There are multiple emission metrics, and the most appropriate metric depends on the application. GHG emission metrics may differ with respect to (i) the key measure of climate change they consider, (ii) whether they consider climate outcomes for a specified point in time or integrated over a specified time horizon, (iii) the time horizon over which the metric is applied, (iv) whether they apply to a single emission pulse, emissions sustained over a period of time, or a combination of both, and (v) whether they consider the climate effect from an emission compared to the absence of that emission or compared to a reference emissions level or climate state."

— ***Notes:*** *Most relative GHG emission metrics (such as the global warming potential (GWP), global temperature change potential (GTP), global damage potential, and GWP*) use carbon dioxide (CO_2) as the reference gas. Emissions of non-CO_2 gases, when expressed using such metrics, are often referred to as 'carbon dioxide equivalent' emissions. A metric that establishes equivalence regarding one key measure of the climate system response to emissions does not imply equivalence regarding other key measures. The choice of a metric, including its time horizon, should reflect the policy objectives for which the metric is applied.*

— The following material is based upon 'Box 7.3: Physical Considerations in Emissions Metric Choice' in Forster et a, (2021).[141]

— *Following AR5, this Report does not recommend an emissions metric because the appropriateness of the choice depends on the purposes for which gases or forcing agents are being compared. Emissions metrics can facilitate the comparison of effects of emissions in support of policy goals. They do not define policy goals or targets but can support the evaluation and implementation of choices within multi-component policies (e.g., they can help prioritise which emissions to abate).* ***The choice of metric will depend on which aspects of climate change are most important to a particular application or stakeholder and over which time horizons. Different international and national climate policy goals may lead to different conclusions about what is the most suitable emissions metric.***[142]

— *Global warming potentials (GWP) and global temperature-change potentials (GTP) give the relative effect of pulse emissions, that is, how much more energy is trapped (GWP)*

[141] Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi: 10.1017/9781009157896.009.
[142] Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M.

or how much warmer (GTP) the climate would be when unit emissions of different compounds are compared. Consequently, these metrics provide information on how much energy accumulation (GWP) or how much global warming (GTP) could be avoided (over a given time period, or at a given future point in time) by avoiding the emission of a unit of a short-lived greenhouse gas compared to avoiding a unit of CO_2. By contrast, the new metric approaches of combined GTP (CGTP) and GWP closely approximate the additional effect on climate from a time series of short-lived GHG emissions, and can be used to compare this to the effect on temperature from the emission or removal of a unit of CO_2.*[143] [144]

— Relevant to net zero GHG emissions goals and short-lived pollutants is the following insight presented by the IPCC: that if short-lived GHGs are declining, they lead to declining levels of warming [attributable to that GHG]. However, if you aggregate GHGs using GWP100, this gives ever-increasing cumulative CO_2-equivalent emissions totals – which implies that warming levels would be rising.

— *When individual gases are treated separately in climate model emulators, or weighted and aggregated using an emissions metric approach (such as CGTP or GWP*) which translate the distinct behaviour from cumulative emissions of short-lived gases, ambiguity in the future warming trajectory of a given emissions scenario can be substantially reduced.* [145] [146] [147] [148]

— *The degree of ambiguity varies with the emissions scenario. For mitigation pathways that limit warming to 2°C with an even chance, the ambiguity arising from using GWP-100 as sole constraint on emissions of a mix of greenhouse gases (without considering their economic implications or feasibility) could be as much as 0.17°C, which represents about one-fifth of the remaining global warming in those pathways (Denison et al., 2019).*

— *If the evolution of the individual GHGs is not known, this can make it difficult to evaluate how a given global multi-gas emissions pathway specified only in CO_2-equivalent emissions would achieve (or not) global surface temperature goals. This is potentially an issue as Nationally Determined Contributions frequently make commitments in terms of GWP-100-based CO_2-equivalent emissions at 2030 without specifying individual gases (Denison et al., 2019).*[149] *Clear and transparent representation of the global warming implications of future emissions pathways including Nationally Determined Contributions could be achieved either by their detailing pathways for multiple gases or by detailing a pathway of cumulative carbon dioxide equivalent emissions approach*

[143] Collins, W.J., D.J. Frame, J.S. Fuglestvedt, and K.P. Shine, 2020: Stable climate metrics for emissions of short and long-lived species-combining steps and pulses. Environmental Research Letters, 15(2), doi: 10.1088/1748-9326/ab6039.

[144] Allen, M.R. et al., 2018b: A solution to the misrepresentations of CO2 -equivalent emissions of short-lived climate pollutants under ambitious mitigation. npj Climate and Atmospheric Science, 1(1), 16, doi: 10.1038/s41612-018-0026-8.

[145] Cain, M. et al., 2019: Improved calculation of warming-equivalent emissions for short-lived climate pollutants. NPJ climate and atmospheric science, 2(1), 1–7, doi: 10.1038/s41612-019-0086-4.

[146] Denison, S., P.M. Forster, and C.J. Smith, 2019: Guidance on emissions metrics for nationally determined contributions under the Paris Agreement. Environmental Research Letters, 14(12), 124002, doi: 10.1088/1748-9326/ab4df4.

[147] Collins, W.J., D.J. Frame, J.S. Fuglestvedt, and K.P. Shine, 2020: Stable climate metrics for emissions of short and long-lived species-combining steps and pulses. Environmental Research Letters, 15(2), doi: 10.1088/1748-9326/ab6039.

[148] Lynch, J., M. Cain, D. Frame, and R. Pierrehumbert, 2021: Agriculture’s Contribution to Climate Change and Role in Mitigation Is Distinct From Predominantly Fossil CO2 -Emitting Sectors. Frontiers in Sustainable Food Systems, 4, 518039, doi: 10.3389/fsufs.2020.518039.

[149] Denison, S., P.M. Forster, and C.J. Smith, 2019: Guidance on emissions metrics for nationally determined contributions under the Paris Agreement. Environmental Research Letters, 14(12), 124002, doi: 10.1088/1748-9326/ab4df4.

aggregated across GHGs evaluated by either GWP or CGTP metric approaches.* [150] [151] [152] *It should be noted that although the Paris Agreement Rulebook asks countries to report emissions of individual GHGs separately for the global stocktake (Decision 18/CMA.1, annex, paragraph 38), which can allow the current effects of their emissions on global surface temperature to be accurately estimated, estimates of future warming are potentially ambiguous where emissions are aggregated using GWP-100 or other pulse metrics.*

— *Although there is significant history of using single-basket approaches, supported by emissions metrics such as GWP-100, in climate policies such as the Kyoto Protocol, multi-basket approaches also have many precedents in environmental management, including the Montreal Protocol (Daniel et al., 2012). Further assessment of the performance of physical and economics-based metrics in the context of climate change mitigation is provided in the contribution of Working Group III to AR6.*

It should be noted that there is an enormous range of different metrics in the aviation literature. Researchers identify research questions, and in many cases will develop a metric to best capture the effects they are studying. As noted by the IPCC (see Box 1) it is not scientifically appropriate to recommend a universal metric, as it depends on the purpose of the comparison being sought. Even within the aviation literature, there is no consensus on a single 'best' metric for aviation, as it will depend on the policy need or application as to which provides the most relevant information.[153] [154] [155]

Here, we have evaluated the basic relative metrics in Table 6 on the next page, as these can be used to calculate CO_2-equivalence, noting that there may be nuance to their application which will depend on the purpose of their use. GWP100 is the most commonly used metric in the wider climate policy community, and is the metric required for reporting to the United Nations Framework Convention on Climate Change.

[150] Cain, M. et al., 2019: Improved calculation of warming-equivalent emissions for short-lived climate pollutants. NPJ climate and atmospheric science, 2(1), 1–7, doi: 10.1038/s41612-019-0086-4.
[151] Collins, W.J., D.J. Frame, J.S. Fuglestvedt, and K.P. Shine, 2020: Stable climate metrics for emissions of short and long-lived species-combining steps and pulses. Environmental Research Letters, 15(2), doi: 10.1088/1748-9326/ab6039.
[152] Lynch, J., M. Cain, D. Frame, and R. Pierrehumbert, 2021: Agriculture's Contribution to Climate Change and Role in Mitigation Is Distinct From Predominantly Fossil CO2 -Emitting Sectors. Frontiers in Sustainable Food Systems, 4, 518039, doi: 10.3389/fsufs.2020.518039.
[153] Irvine, E.A., Hoskins, B.J. and Shine, K.P. (2014) 'A simple framework for assessing the trade-off between the climate impact of aviation carbon dioxide emissions and contrails for a single flight', Environmental Research Letters, 9(6). Available at: https://doi.org/10.1088/1748-9326/9/6/064021
[154] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834.
[155] Fuglestvedt, J. et al. (2023) 'A "greenhouse gas balance" for aviation in line with the Paris Agreement', Wiley Interdisciplinary Reviews: Climate Change, 14(5). Available at: https://doi.org/10.1002/wcc.839.

Table 6: Summary of key features of relative metrics.

GWP100, GWP50, GWP20: Pulse based, time-integrated radiative forcing-based metric	
What it captures	The amount of energy added to the climate system from an emission (or other forcing agent) averaged over the time period stated, expressed relative to the same mass of CO_2 being emitted. When applied to contrails, which cannot be expressed as a mass of emissions, GWP is sometimes defined as radiative forcing per km flown, per flight, or total flights per annum.[156]
Features	Can specify different time periods dependent on what time period you are interested in (currently common to use 20 years for near term effects or 100 years for longer term effects). Using multiple time horizons helps to capture the fact that the values of GWP20 and GWP100 will vary strongly for short lived forcings, as they cause strong warming in the short term, but not in the long term. GWP100 is approximately equal to GTP20 for black carbon, and GTP40 for methane; i.e. GWP100 captures temperature effects approx. 20 years after a black carbon emission, or approx. 40 years after a methane emission.[157] Represents the effect of a pulse/one-off emissions relative to no emission. It does not capture that declining short lived forcings leads to RF and temperatures declining.
GTP100, GTP50, GTP20: Pulse-based, time horizon temperature change based metric	
What it captures	The temperature change following the emission at the time horizon, expressed relative to the temperature change if the same mass of CO_2 was emitted. i.e. if GTP100 is 4, then there is 4x as much warming between the emission and 100 years after from the gas compared to the same mass of CO_2 being emitted.
Features	Can specify different time periods (commonly 20 years for near term effects or 100 years for longer term effects). Using multiple time horizons helps to capture the fact that the values of GTP20 and GTP100 will vary strongly for short lived forcings, as they cause strong warming in the short term, but not in the long term. E.g. using GTP20 to will assign a larger CO_2-equivalent value to contrails than GTP100. Represents the effect of a pulse/one-off emissions relative to no emission. It does not capture that declining short lived forcings leads to RF and temperatures declining.

[156] Fuglestvedt, J.S., Shine, K.P., Berntsen, T., Cook, J., Lee, D.S., Stenke, A., Skeie, R.B., Velders, G.J.M., Waitz, I.A., 2010. Transport impacts on atmosphere and climate: Metrics. https://doi.org/10.1016/j.atmosenv.2009.04.044
[157] Allen, M.R. et al., 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. Nature Climate Change, 6(8), 773–776, doi: 10.1038/nclimate2998.

GWP*: Step-pulse based, additional warming-based metric	
What it captures	GWP* bases its equivalence an approximation of temperature change that occurs from a short-lived pollutant emission. It is denoted a 'step-pulse' metric because it was developed from the observation that a one-off (pulse) CO_2 emission gives the same trajectory of warming as a step-change in emissions of a short-lived pollutant. It is also referred to as a 'warming equivalent' metric as it effectively 'works backwards' to find the CO_2 emission that would give the same temperature outcomes[158].
Features	Approximates the results from a climate model in one equation Captures the temperature change that an emission causes at that point in time. This means that an emission of the same magnitude at different times (e.g. in the pre-industrial time, or in 2050) will have different 'warming equivalent' amounts of CO_2. This is a reflection of what would be found by a climate model. It captures that declining short lived forcings leads to both RF and temperatures declining.

[158] FAO. 2023. Methane emissions in livestock and rice systems – Sources, quantification, mitigation and metrics. Rome. https://doi.org/10.4060/cc7607en

5.2.1 Stakeholder workshop insights

Stakeholders were interested in simplicity and consistency when defining metrics, noting that it is not about identifying the unique correct metric, rather a case of desiring one consistent, meaningful agreed metric. This will become key for reporting purposes at national, and supranational / international, level (e.g., the EU). It serves as a means of differentiating the magnitude of actions from different decisions and mitigation strategies. Stakeholders expressed the need to be able to compare different emissions via the agreed metrics, especially where trade-off may be required between emissions in management, and that understanding the absolute impact was key.

5.3 Pros and cons of identified existing metrics to measure the non-CO_2 impacts of aviation

Metrics are used to aggregate or compare the impact of different types of emissions and forcings. This is done by putting them all on to one scale, typically quoted relative to CO_2, hence the term 'CO_2-equivalent'. This would allow consideration as to whether trade-offs have a net benefit, e.g., reducing contrail formation through a mitigation option which requires a greater fuel use and therefore greater CO_2 emissions. The difficulty is that equivalence is not uniquely defined, as explained by the IPCC (see Box 1), as each forcing will have an effect over a different timescale and there are a range of impacts and time periods that could be compared. Here, we explore pros and cons of metrics in set out in Table 6.

Depending on what timescale is under consideration, for example, trade-offs may appear more or less beneficial. In extreme examples, use of different metrics of equivalence have been shown to increase or decrease temperature in 'equivalent' emissions scenarios.[159] This is because the impact of a short-lived forcing (like methane, NOx or a contrail) has a large impact over the period it is present, but then the effect diminishes. A single-value metric (like GWP20, GWP50, GWP100, GTP20, GTP50, GTP100) will provide a static valuation of a short-lived forcing, which will undervalue its impact in the short-term and overvalue it in the long term. Hence, if using a single metric but you are interested in effects over a range of different time periods, the equivalence will not represent all time periods well. A potential risk with using a short-term metric like GWP20 which places a high value on a short-lived forcing is of unintended consequences if long- and short-lived forcings are treated together in one basket. For example, you could achieve a given reductions target by cutting short lived pollutants only, and by only a relatively small amount as each ton of emission is weighted so highly. This would effectively mean overall emissions reductions compared to using GWP100, and in effect delaying action on CO_2

[159] Allen, M.R. et al. (2022) 'Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets', npj Climate and Atmospheric Science, 5(1), pp. 18–21. Available at: https://doi.org/10.1038/s41612-021-00226-2.

because you emission target is so easily achieved using the short lived GHGs weighted with GWP20. In the long run that is almost certainly, worse for climate.

Lee *et al*, 2021 tabulate a range of metrics (GWP20, GWP50, GWP100, GTP20, GTP50, GTP100 and GWP*) and corresponding CO_2-equivalent emissions for 2018 aviation emissions using each metric.[160] They show that the ratio of total $CO_{2\text{-}e}$ emissions to CO_2 emissions varies depending on which metric is used to calculate $CO_{2\text{-}e}$, from 1.0 (using GTP50) to 4.0 (GWP20). Using GWP*, which represents how much the emission affects temperature at that time, to calculate the CO_2-e, gives a ratio of 3.0, implying that the warming effect of aviation when including non-CO_2 impacts is three times that of CO_2 emissions only.

Another key point made by Lee *et al*, 2021 is that, based on IPCC statements, to halt anthropogenic global warming, aviation (or any and all sectors) need to reach and sustain net-zero CO_2 emissions as well as declining net non-CO_2 forcings. Both are required.[161]

Lee *et al* (2023) note that use of GWP100 does not reflect temperature outcomes for short lived forcings, and so its use related to the Paris Agreement temperature goals is 'slightly incoherent'.[162] If GWP100 continues to be used in assessing progress towards the Paris Agreement, then emissions targets that use GWP100 will not reflect warming outcomes. GWP100 under-represents the warming generated by increasing short-lived forcings.

Lee *et al* 2023 also note that if governments changed to targeting impact on temperature (not GWP100-defined CO_2-e emissions) then this would incentivise reducing short-lived forcing reductions and penalise increases in the same, relative to targeting GWP100-defined CO_2-e emissions. [163] Ways to target impact on temperature include using GWP* (or other 'warming-equivalent' or 'flow-based' metric) or a climate model as discussed below.

Allen *et al*, 2022 recommend that short lived pollutant emissions targets or reporting are separated from long lived emissions, in order that temperature implications are clear.[164]

In practice, if an aggregated CO_2-equivalent target were made for aviation, or indeed a net- zero target which required CO_2-based offsetting, then each different

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[160] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

[161] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

[162] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740. https://doi.org/10.1039/D3EA00091E

[163] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740. https://doi.org/10.1039/D3EA00091E

[164] Allen, M.R. et al. (2022) 'Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets', npj Climate and Atmospheric Science, 5(1), pp. 18–21. Available at: https://doi.org/10.1038/s41612-021-00226-2.

commonly used metric would give rise to a different amount of allowable emissions, and thus different temperature outcomes[165].

One way to avoid this ambiguity is to avoid setting an aggregated CO_2-equivalent emissions target entirely[166]. Instead, a limit to the amount of emissions for each gas could be identified, and a limit to the ERF arising from contrails and contrail-cirrus. Or simply a limit to the total amount of ERF.

Another way would be to provide aggregation using a 'warming-equivalent' or 'flow-based' metric, which captures the global warming effects of short-lived forcings more accurately than standard metrics. GWP* is an example of this type of metric which has been applied to aviation emissions[167]. GWP* has two terms, which capture the differing short term and long-term effects of short-lived forcings. It accounts for present day trends in the aviation forcing, as increasing forcing trends drive up temperatures whereas decreasing forcing trends reduce temperatures. It does therefore require a careful definition of the question being asked so that it is applied to the data correctly.

GWP*, or a climate model, could be used to frame aviation's contribution to global warming at different times, e.g. at present day, 2035, 2050, 2100 under different proposed mitigation plans.

Further discussion on the different metrics and how they can best be used will be explored when considering which are most fit for purpose (section 5.5). This evaluation will combine how the industry needs to use the measures to monitor mitigating actions and understanding of the research gaps to consider the best options for future work. It is expected that different metrics may be beneficial for different policy approaches and mitigation approaches. For example, if the requirement is to minimise near-term global warming, then without a thorough analysis of which is an appropriate metric for the context, there may be unintentional outcomes; e.g. choosing GWP20 could result in perverse outcomes if using offsetting between short- and long-lived gases.[168] For example, GWP20 gives a higher CO_2-equivalent value to any short lived forcing than GWP100. Lee et al. (2021)'s weighting of total aviation effects relative to CO_2 only effects of aviation is 4.0 using GWP20 compared to 1.7 using GWP100, and 1.0 using GTP50. In other words, valuing aviation using GWP20 makes it worth 4 times as much CO_2-

[165] Fuglestvedt, J., Lund, M. T., Kallbekken, S., Samset, B. H., & Lee, D. S. (2023). A "greenhouse gas balance" for aviation in line with the Paris Agreement. WIREs Climate Change, 14(5), e839. https://doi.org/10.1002/wcc.839

[166] Allen, M.R., Peters, G.P., Shine, K.P., Azar, C., Balcombe, P., Boucher, O., Cain, M., Ciais, P., Collins, W., Forster, P.M., Frame, D.J., Friedlingstein, P., Fyson, C., Gasser, T., Hare, B., Jenkins, S., Hamburg, S.P., Johansson, D.J.A., Lynch, J., Macey, A., Morfeldt, J., Nauels, A., Ocko, I., Oppenheimer, M., Pacala, S.W., Pierrehumbert, R., Rogelj, J., Schaeffer, M., Schleussner, C.F., Shindell, D., Skeie, R.B., Smith, S.M., Tanaka, K., 2022. Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. npj Climate and Atmospheric Science 5, 18–21. https://doi.org/10.1038/s41612-021-00226-2

[167] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, p.117834.

[168] Allen, M., Tanaka, K., Macey, A., Cain, M., Jenkins, S., Lynch, J., Smith, M., 2021. Ensuring that offsets and other internationally transferred mitigation outcomes contribute effectively to limiting global warming. Environmental Research Letters 16, 074009. https://doi.org/10.1088/1748-9326/abfcf9

equivalent emissions (4128 Tg CO_2 yr^{-1}) as using GTP50 1035 (Tg CO_2 yr^{-1}). If a target is to reduce CO_2-equivalent emissions by an absolute amount or a fraction, say 20%, the ability to do that using non-CO_2 will depend on which metric is used. Removing a small amount of the total non-CO_2 effect would result in a larger amount of CO_2-equivalent cuts. Therefore, a smaller cut in actual radiative forcing leads to the same progress towards that 20% reduction in total CO_2-equivalent emissions. Therefore, in this example, giving a higher value to short lived forcings leads to a smaller reduction in radiative forcing on achievement of the emissions target. This is an example of why it is valuable to separate out long- and short-lived forcings, rather than aggregate them into one basket.

5.4 An evaluation of potential methods and metrics to measure the non-CO_2 impacts of individual flights

Climate metrics were developed to provide approximate ways of comparing the climate impact of different greenhouse gases on global and multi-year scales. Some compounds (e.g., contrails, NOx) do not mix well in the atmosphere due to their short residence times. This is scientifically problematic as one cannot simply assume that local climate impacts scale linearly to global ones. In addition, climate impact depends on the time period being considered, and are we worried about the peak or the summation of emissions? The ideal metric would be used to compare effects happening over different scales and different time periods. This is not possible if using GWP100 in the typical way, as it is formulated for the global mean over 100 years. This is especially problematic when comparing the climate impact of short-lived and regional forcings (contrail-cirrus, NOx) with those of long-lived, global forcings (CO_2).

These challenges are well recognised by atmospheric researchers in the field. Fuglestvedt *et al.* (2023) have noted that uncertainties in the estimation of non-CO_2 impacts of aviation, and the propagation thereof into metrics, could mean funds are spent on mitigation which does not deliver the intended benefits.[169] Some are focussing on quantifying the factors which lead to the uncertainties in the estimates of global contrail-cirrus forcing and these are reviewed in Lee *et al.* (2023).[170]

The issue of whether measures should be introduced in the near-term based on non-CO_2 effects represented using metrics is contentious with some feeling that the science underlying the contrail-cirrus should be significantly improved, and that global mean metrics are not suitable for individual flights.[171] The main concern is that additional CO_2 may be emitted as a result of contrail-cirrus avoidance approaches which do not actually avoid contrail-cirrus. Shine and Lee (2023) set out some

[169] Fuglestvedt, J., Lund, M. T., Kallbekken, S., Samset, B. H., & Lee, D. S. (2023). A “greenhouse gas balance” for aviation in line with the Paris Agreement. WIREs Climate Change, 14(5), e839. https://doi.org/10.1002/wcc.839
[170] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.
[171] Shine and Lee, Contrails versus CO_2. Contrails Avoidance – Challenges, Presentation at Sustainable Skies Conference: Contrails in Focus, Eurocontrol, November 7-8 2023. https://www.eurocontrol.int/event/sustainable-skies-conference-contrails-focus

standards by which the introduction of contrail-cirrus avoidance measures could be introduced.[172] These are applied to each individual flight rather than to the average of such flights.

In parallel, analyses of when and where contrails form have shown that contrail-cirrus only form during a small number of flights. For example, Teoh *et al.* (2023) used real flight data to estimate that 2% of flights accounted for 80% of the total radiative forcing from contrails in 2019[173]This finding shows the potential to significantly reduce the contrail-cirrus climate forcing by targeting the mitigating actions on a small subset of flights and regions associated with strongly warming contrails. This makes the job of rerouting less disruptive to current operations that it might have been, but it does not assess when and where re-routings are advisable from a climate perspective.

Bellouin (2023) looked at the use of metrics in assessing the impact of individual flights over the North Atlantic, considering three families of metrics.[174] The decision to reroute is found to be weakly dependent on the climate metric used but quantifying the climate benefit is strongly dependent on it. In this case, an airline can decide to take such measures purely to provide a benefit to climate.

5.5 Assessment of suitability of metrics for policy design

The UN Food and Agriculture Organization (FAO) published a report on agricultural methane, mitigation and metrics in 2023, which includes a recommendation for how to approach metric choice involving the agricultural community, governments and the scientific community.[175] While this was tailored to agricultural methane (a short-lived greenhouse gas), the issues are applicable when considering any short-lived climate forcing, such as the non-CO_2 forcings from aviation. Based on this report, the following points should be considered when trying to identify the most suitable metric for any particular policy question or goal:

5.5.1 Define your question

A clear definition of the question under consideration is critical to determining an appropriate metric to use. Sometimes there will be multiple questions or goals so a hierarchy may be required. A clear example of this is that if you wish to identify the most cost-effective flight path, you need to include costs in the metric. If you wish to identify the flight path with least CO_2 emissions, you could simply consider CO_2 emissions. If you wish to identify the flight path with minimised climate impacts, then

[172] Shine and Lee, Contrails versus CO_2. Contrails Avoidance – Challenges, Presentation at Sustainable Skies Conference: Contrails in Focus, Eurocontrol, November 7-8 2023. https://www.eurocontrol.int/event/sustainable-skies-conference-contrails-focus

[173] Teoh, R., Engberg, Z., Schumann, U., Voigt, C., Shapiro, M., Rohs, S., and Stettler, M.: Global aviation contrail climate effects from 2019 to 2021, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-1859, 2023.

[174] N. Bellouin, CO2 equivalence metrics and contrail avoidance, Presentation at Sustainable Skies Conference: Contrails in Focus, Eurocontrol, November 7-8 2023. https://www.eurocontrol.int/sites/default/files/2023-11/2023-11-07-contrails-conference-session-002-bellouin-co2-equivalence-metrics-and-contrail-avoidance.pdf

[175] FAO. 2023. Methane emissions in livestock and rice systems – Sources, quantification, mitigation and metrics. Rome. https://doi.org/10.4060/cc7607en

you need to include both CO_2 and non- CO_2 forcings. In this latter case, you would also need to specify at what time(s) you wish to make this evaluation, as impacts from contrail-cirrus are short-lived. There are further details which need to be explicitly considered in order to articulate a well-defined question, as described in the following points.

5.5.2 Existing requirements for metrics

In some cases, there will be an external requirement for use of a specific metric. Even in such a case, there may still be value in exploring other metrics in addition. For example, to understand outcomes on different timescales, or to look at a wider range of impacts which may be important, though unregulated.

5.5.3 Time frame

When short- and long-lived forcings are being compared (e.g., contrails-cirrus and CO_2), the time frame at or over which they are compared can make a substantial difference. For example, the warming caused by emitted CO_2 from a single flight persists long term, for hundreds of years. However, the impact from contrail-cirrus produced would be strongest in the first year and would decline after that. It is therefore possible that evaluating impacts for the short term only would de-prioritise long term CO_2 impacts (or vice-versa).

One option to combat this is to use a pair of time horizons when assessing short-lived forcings, e.g. use 20 and 100 year metrics, so that both timescales are captured. This would identify where there was a discrepancy in the conclusions using the two different metrics, thus warranting more careful analysis.[176] [177] For example, if a policy will generate a benefit at 20 years, and a harm at 100 years, this could be considered in the planning.

Another option could be to demonstrate the impact of a future scenario on climate change. This could be done using a climate model, or a metric which is in effect a very simple climate model emulator. These metrics are sometimes called warming-equivalent metrics (IPCC AR6 WGI Ch7) and include GWP* and CGTP (Combined Global Temperature-change Potential).[178] These metrics are able to represent the additional warming (if any) from emissions over a chosen time period. For example, implementation of a policy could be modelled for the coming 100 years, and so any competing effects would be seen – such as the short term benefit and long term

[176] FAO. 2023. Methane emissions in livestock and rice systems – Sources, quantification, mitigation and metrics. Rome. https://doi.org/10.4060/cc7607en

[177] Ocko, I.B., Hamburg, S.P., Jacob, D.J., Keith, D.W., Keohane, N.O., Oppenheimer, M., Roy-Mayhew, J.D., Schrag, D.P. & Pacala, S.W. 2017. Unmask temporal trade- offs in climate policy debates. Science, 356(6337): 492–493. https://doi.org/10.1126/ science.aaj2350

[178] Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D.J., Mauritsen, T., Palmer, M.D., Watanabe, M., Wild, M. & Zhang, H. 2021. The Earth's energy budget, climate feedbacks, and climate sensitivity. In: V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu & B. Zhou, eds. Climate change 2021: The physical scienc
basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change
, pp. 923–1054. Cambridge, UK & New York, USA, Cambridge University Press. https://doi.org/10.1017/9781009157896.001

harm mentioned in the previous example. More context on the distinction between GWP100 and warming-equivalent metrics follows in the next section.

Discount rates are used to put a present value on costs and benefits that will occur at a later date. They calculate how much guarding against future carbon emissions is worth to us now, weighing up the benefits future generations would experience against the costs that today's society would have to bear. The same concept can be applied to GHG emissions and how much value we assign them. In effect, by putting a higher weight on future generations, a lower discount rate implies more short term abatement efforts and lower global temperature increases. For example, one study estimated GWP100 was representative of a roughly 3% discount rate, and GWP20 around 13%.[179]

5.5.4 Context and counterfactual baseline

There is a fundamental distinction between a warming equivalent approach, and a single-number metric. A single number metric, such as GWP100, assigns one specific value to every unit of non-CO_2 forcing. In this sense, GWP100 uses a counterfactual of no activity (i.e., no emissions or radiative forcing), and represents the impact of introducing an activity.

Warming-equivalent metrics take a different approach. They start from a particular time point and consider the effect on global warming from that point in time (knowing what the activity up until that point has been), and they approximate the impact on global warming of the assumed change in activity. Therefore, this type of metric is capturing the change in warming relative to the initial year under consideration (i.e. additional warming since the baseline year). An example of this type of metric applied to aviation is GWP*.[180] [181]

This approach can show that, for example, if non-CO_2 forcing declines between 2024 and 2050, then the warming from non-CO_2 forcing will reduce, and different metrics will show different impacts. For example, the 'CO_2-equivalent' emission over this period would be negative because the only way for CO_2 to cause a decline in temperature is for it to be removed from the atmosphere. In comparison, under this scenario, GWP100 would give a declining, but non-zero, $CO_{2\text{-}e}$ emission. If these non-CO_2 forcings were eliminated entirely, the temperature would be even lower, and the '$CO_{2\text{-}e}$' emissions would be even more negative. In comparison, GWP100 here would give zero emissions.

To try and represent a single flight, an option to consider for GWP* would be to represent that flight's impact only, i.e., this would assume no activity before the flight.

[179] Sarofim, M.C. & Giordano, M.R. 2018. A quantitative approach to evaluating the GWP timescale through implicit discount rates. Earth System Dynamics, 9(3): 1013–1024. https://doi.org/10.5194/esd-9-1013-2018
[180] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, p.117834.
[181] M Klöwer et al 2021 Environ. Res. Lett. 16 104027 DOI 10.1088/1748-9326/ac286e

This would then mean that the flight would add some radiative forcing, and thus the CO_2-equivalent emissions calculated with GWP* would always be positive. This is more akin to how the single-number metrics like GWP and GTP and would represent the warming caused by an individual flight occurring. Its accuracy will depend upon the applicability of the underlying model assumptions to that particular flight, thus the same problems with using a global metric for an individual flight remain.

These types of differences illustrate that GWP100 and GWP* represent fundamentally different concepts, and the most appropriate one to use would depend on whether you were wanting to represent the additional warming caused over a specified time period (GWP*) or to represent the additional energy added to the system over a century compared to avoiding that activity (GWP100).

5.5.5 Comparability and transparency

GWP100 is often cited as a useful metric for comparability with other work, given it is the most commonly used metric. Hence even when other metrics are used to illustrate key impacts, GWP100 is often used in addition for comparability and transparency. Any notable discrepancy between another metric and GWP100 is an opportunity to gain insight into why.

5.5.6 Other considerations specific to aviation

Avoidance of contrail-cirrus formation for aircraft using any fuel capable of forming contrail-cirrus requires changes in the flight plans. Airlines aim to minimise the cost of each flight when developing flight plans. Fuel use is the main variable cost and so there is a general tendency to minimise CO_2 emission. However, a number of other costs are also included, not all of which can be readily converted to a CO_2-e emission using a climate emission metric. First, real-time delays can lead to non-optimal routes. Second, airlines make decisions based on the total cost of the flight which also includes air traffic control charges, compensation for late arrivals, staff costs, etc. Third, the decision-making procedures may not themselves be optimal depending on how they are constructed. Identifying instances where the CO_2 and fuel could be better 'spent' on contrail-cirrus avoidance would undoubtedly be beneficial. Identifying how the climate impact could be incorporated into the individual decision-making systems is fundamental.

5.6 A common tool for evaluating CO_2 and non-CO_2 climate impacts

In an ideal world, metrics should be used to inform the response to the specific problems under consideration. For example, engine manufacturers making decisions about investments in new engine technologies which will have impacts for several decades. Airlines and other groups are potentially more interested in actions that have a more immediate impact such as reducing contrail-cirrus formation. Governments and the public are concerned about the overall impact of aviation on climate, possibly at all timescales. Decisions to achieve these varied aims are best answered by different metrics. It is hard to see how this can be achieved with a single metric when short lived forcings are a key component. To avoid ambiguity on this front, Allen et al., (2023) recommended a parallel track approach of separating long-lived and short-lived pollutants. [182]

Discussions at the aviation stakeholder meeting emphasised the desire for (i) something simple and, preferably, (ii) the same metric across the board. As discussed, these two criteria cannot both be met. So, a different approach which meets the needs of all stakeholders and has a firm scientific basis is required to provide a firm and commonly accepted basis for decision-making. One approach would be to jointly define a common range of metrics which can be used to address different issues with a range of timescales in the atmosphere and the industry.

Identifying the suite of metrics would require more structured discussion of the strengths and weaknesses of metrics and how they relate to stakeholders (as outlined in Appendix B). The suite of metrics would allow individual stakeholders to consider and use those that are more relevant to them. The range of metrics would show the implications of flights or mitigation actions at different timescales, and with different choices of discount rates. Inclusion of GWP100 would seem essential to provide a common basis for understanding, given it is the metric used for national reporting to the UN under the Paris Agreement.

5.7 Conclusion

The evaluation of existing methodologies and metrics for measuring and monitoring the non-CO_2 impacts of aviation is a complex task due to several reasons. Firstly, the climate impact of different emissions and forcings varies over time and space. For example, contrails have a short residence time, and their impact is regional, while CO_2 has a long residence time, and its impact is global. Secondly, the choice of metric depends on the policy need and goal. For instance, if the goal is to minimise near-term global warming from aviation, then metrics like GTP20 may be more appropriate, while if the goal is to minimise long-term temperature change, then metrics like GTP100 may be more suitable; the appropriate policy should be measured with the appropriate metric. A more complete understanding at a range of timescales would require a warming-equivalent metric.

Given these challenges, a single metric that can capture all aspects of the non-CO_2 impacts of aviation is not feasible. Lee et al. showed that he ratio of total CO_2-equivalent emissions to CO_2 emissions from aviation in 2018 varied from 1.0 to 4.0, depending on the metric. Instead, a suite of metrics can be developed to address this issue. It is also recommended that short- and long-lived forcings have separate

[182] Allen, M.R., Peters, G.P., Shine, K.P., Azar, C., Balcombe, P., Boucher, O., Cain, M., Ciais, P., Collins, W., Forster, P.M., Frame, D.J., Friedlingstein, P., Fyson, C., Gasser, T., Hare, B., Jenkins, S., Hamburg, S.P., Johansson, D.J.A., Lynch, J., Macey, A., Morfeldt, J., Nauels, A., Ocko, I., Oppenheimer, M., Pacala, S.W., Pierrehumbert, R., Rogelj, J., Schaeffer, M., Schleussner, C.F., Shindell, D., Skeie, R.B., Smith, S.M., Tanaka, K., 2022. Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. npj Climate and Atmospheric Science 5, 18–21. https://doi.org/10.1038/s41612-021-00226-2

policies and targets, given they affect climate on different timescales. The suite of metrics could potentially include some of the metrics discussed above, or others, contingent on stakeholder discussions, each providing different insights into the climate impact of aviation. Stakeholders can then prioritise relevant metrics based on their specific policy needs and goals.

The metric choice process requires co-development, including structured discussions on policy requirements and metric strengths and weaknesses. This involves engaging with experts, policymakers, and stakeholders to understand their needs and concerns. It is also important to incorporate lessons learned from real-world planning and practice to ensure that the range of metrics are practical and fit-for-purpose.

By employing appropriate climate metrics and considering their strengths and limitations, policymakers and stakeholders can make informed decisions to mitigate climate change effectively. This will require a collaborative effort to develop a common understanding of the non-CO_2 impacts of aviation and to identify the most suitable metrics for different policy needs and goals.

6 Gap assessment and policy considerations

6.1 Introduction

This chapter provides a detailed analysis of key findings from secondary research, focusing on key research gaps and policy considerations for non-CO_2 impacts from aviation. Conducting a gap assessment is crucial for identifying knowledge gaps and uncertainties in scientific understanding, guiding policymakers and researchers in prioritising research efforts and resource allocation.

Knowledge gaps are presented against the impact areas of contrails (6.2.1), NOx (6.2.4) and aerosol cloud interactions (6.2.5). Recommendations for research areas are also given based on the literature review outputs.

There are further challenges in observing and measuring aspects of non-CO_2 impacts, including water vapour, ice supersaturated regions, contrail cirrus, and contrail cirrus persistence. Developing more robust tools for observations is necessary.

While many mitigations have been explored, there are gaps in understanding their impact. Research recommendations include:

- Improving weather forecasting capability
- Evaluating navigational contrail avoidance
- Investigating the impact of sustainable aviation fuel (SAF) on contrail cirrus
- Exploring mitigation strategies that reduce soot emissions
- Improving modelling around the ice nucleation ability of aviation soot particles to improve estimates of the RF resulting soot-cloud interactions.

Gaps also exist within the methods and metrics used for non-CO_2 impacts. With stakeholders emphasised the need for easy-to-use methods and metrics which could provide comparisons between non-CO_2 and CO_2 impacts. Methods and metrics are necessary to enable effective delivery and measurement of mitigations. Operational constraints and validation emerged as critical areas, highlighting the importance of independent validation tools and improved global satellite validation. However, section 3 details the challenges of identifying and implementing a single metric for this purpose. In further developing or defining a metric or suite of metrics to use, the operational constraints and stakeholders needs must be considered.

Finally, Government intervention was deemed pivotal, stressing the necessity for holistic guidance, clear parameters and aligned incentives. Government intervention is essential to catalyse emission reduction. Early policy interventions, especially in advancing airspace complexities and incentivising key investments, were highlighted as critical steps.

Future focus areas

The report suggests focusing on:

- The scalability of contrail management
- Technological advancements in aircraft instrumentation
- Collaboration with meteorological offices

The above are important for enhancing data accuracy and advancing emission reduction strategies. Reducing uncertainties associated with future NOx impacts through improved modelling and understanding of spatial and temporal influences is also recommended.

While significant gaps exist in understanding non-CO_2 impacts, methods and metrics to calculate impact, and mitigation strategies, trials of mitigation approaches have shown promising signs of potential. Improved observations, reduced uncertainties, and further research are necessary to inform policy decisions and develop effective strategies to mitigate non-CO_2 impacts from aviation.

6.2 Knowledge gaps that require further research

Conducting a gap assessment on literature for non-CO_2 impacts from aviation is of paramount importance for policy considerations. It enables the identification of knowledge gaps and uncertainties in the scientific understanding of these impacts, guiding policymakers and researchers in prioritising research efforts and allocating resources efficiently.

Knowledge gaps have been identified in five broad categories:

1. The climate impact of contrails
2. Observations (relevant to contrails)
3. Contrail mitigation strategies
4. The climate impact of NOx
5. The climate impact of aerosol-cloud interactions

The gaps include both gaps in research and in lack of consensus/uncertainty in the estimates of impact and mitigations. For each category, a description of the research gaps is given, followed by a list of recommended areas for future research.

In section 4.3, an exploration is made into past and current research projects. Most of the research recommendations here require many model studies or experiments in order to reach an academic and industry consensus that the gaps have been filled – therefore the presence of research programs in similar spheres should not necessarily preclude other research being done in this area. On the other hand, it may provide an opportunity for UK funded projects and programs to collaborate with others and contribute to the larger shared goal of reducing uncertainty around the radiative impact of non-CO_2 and devising methods to mitigate them.

6.2.1 Knowledge gaps in quantifying the climate impact of contrails

As has been noted in this report, there is considerable uncertainty around the global RF resulting from contrails.[183] Lee et al., 2021 estimated the uncertainty in the aviation non-CO_2 terms to be 8 times larger than the uncertainty in the CO_2 forcing term.[184] Whether contrail cirrus is the largest non-CO_2 forcing term remains largely uncertain.[185] All work improving the confidence of the climate impact of contrails will help in assessing their importance relative to CO_2 emissions, which in turn aids in assessing both mitigation options (as some may involve a CO_2 penalty), and in guiding government and industry in their resource allocation. In this section, a number of topics, where there are gaps in understanding or research, are described in Table **7** on the next page.

[183] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, p.117834.
[184] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834
[185] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.

Table 7: Summary of research gaps identified around quantifying the climate impact of contrails.

Research gap	Summary
Modelling contrail cloud physics and radiative processes	The size range in contrail modelling varies from very small soot particles to several kilometre wide contrail cirrus clouds. Cloud physics modelling is important for tracking contrail properties, which are then fed into radiative transfer models which calculate the RF. Capturing the cloud physics and radiative processes accurately is challenging, especially if there are limits on computation time imposed by operational requirements, but important to improve confidence in RF estimates.
Modelling the impact of cloud overlap on contrail radiative forcing	The presence of other clouds above or below a contrail has a significant impact on its RF – this requires further modelling.
Modelling the cloud dehydrating effect on contrail climate impact	Lee et al., 2023, stated that there is a general consensus of the RF/ERF ratio to be about a half. More confidence in narrowing down this value would be helpful in assessing the climate impact of contrails.
Investigating the conditions necessary for contrail persistence	Precision on this would improve the accuracy of models predicting global contrail RF from historical weather data.
Modelling the surface temperature impact of contrails	Additional work in this field will improve confidence in evaluating the climate impact of contrails, which can perhaps be split into three parts: Estimating global contrail RF Estimating global contrail ERF (through a scale factor or higher fidelity modelling to replace the above) Estimating the subsequent impact on global surface temperatures
Modelling ISSR and cirrus clouds in General Circulation Models	General Circulation Models are large-scale models which can be used to estimate the global RF of contrails. They can have very large grid sizes (the spatial resolution of weather variables in the model) which is a challenge for modelling cloud microphysics.
Number of contrail models	It has been highlighted in the literature that more contrail models would be beneficial to progress.

Modelling contrail cloud physics and radiative processes

Contrail models have large uncertainties due to a lack of physical understanding and quantification of basic processes and their dependencies, including cloud physics and radiative processes.[186] The cloud physics affect the RF by setting the size, shape and number of ice crystals. Therefore, uncertainty in RF estimates comes from both the inputs to those equations (depending on cloud physics), and the parameterisations used to estimate the RF itself.

As noted by Lee et al., 2023, the contrail cirrus net RF is a relatively small residual of LW radiation versus SW radiation terms (which are warming & cooling respectively).[187,188,189] and therefore requires high confidence in the parameterisations and models used to calculate both terms.

An important problem to be aware of is that in order to run contrail models (which track ice physics and radiation) in an operational setting for contrail mitigation, they need to be fairly inexpensive computationally, which limits how detailed the physical models can be. The same also applies for simulating contrails globally for annual RF estimates. The task for academia/the industry is therefore to continue to work on developing accurate parameterisations of complicated processes which can be used in models like CoCiP/pycontrails and in General Circulation Models. This can be driven by observations and more computationally expensive but higher fidelity modelling (e.g. Lewellen et al., 2014).[190]

Table 8, on the next page, provides examples of particular areas where there are gaps in knowledge. The list of gaps given in the appendix of Lee et al., 2021, was the starting point for this summary.[191]

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[186] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. *Environmental Science: Atmospheres*, *3*(12), pp.1693-1740.

[187] Schumann et al., 2012 figure 4 illustrates the uncertainty associated with their RF model which is implemented in *pycontrails*.

[188] Meerkötter, R., Schumann, U., Doelling, D.R., Minnis, P., Nakajima, T. and Tsushima, Y., 1999, August. Radiative forcing by contrails. In *Annales Geophysicae* (Vol. 17, pp. 1080-1094). Springer-Verlag.

[189] To illustrate this (numbers not representative of any real estimates), if the warming term of a contrail is $+100 \pm 10Wm^{-2}$ (10% uncertainty), and the cooling term $-60 \pm 10Wm^{-2}$ (17% uncertainty), the net RF term will be $40 \pm 20Wm^{-2}$, ie 50% uncertainty.

[190] Lewellen, D.C., Meza, O. and Huebsch, W.W., 2014. Persistent contrails and contrail cirrus. Part I: Large-eddy simulations from inception to demise. *Journal of the Atmospheric Sciences*, *71*(12), pp.4399-4419.

[191] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

Table 8: Examples of knowledge gaps in contrail cloud physics and radiative transfer models

Uncertainties in contrail/ice cloud physics	Uncertainties in radiative transfer calculations
Model calculations of contrail cirrus RF are strongly sensitive to model parameters such as the ice crystal size, the contrail cross-sectional area and the lifetime of contrails/contrail cirrus.[192] More observational data on the macro- and microphysical properties of contrail/contrail cirrus would help constrain these model parameters – see section 4.2.2 below.	Multiple parameters in the contrail RF model developed by Schumann et al., 2012, depend on the ice crystal geometry (see Table 1 of that publication).[193] Schumann et al., 2011, suggested a relationship in which the distribution of contrail ice crystal geometry is a function of the volume mean radius. This was guided by observations and further literature.[194] However, more research in this field is necessary to improve confidence.
Some fraction of ice crystals can be lost in the contrail vortex phase and there is uncertainty around this fraction.[195] Contrail cirrus RF is sensitive to ice crystal numbers in young contrails.[196] Therefore, improved confidence is beneficial to driving down uncertainty.	Lee et al., 2021, reported that there is uncertainty around the radiative impact due to the presence of soot within contrail cirrus ice crystals (present since they lead to contrail formation).[197] They noted that the impact of the soot cores was likely to increase RF estimates, citing Liou et al., 2013.[198]

Modelling the impact of cloud overlap on contrail radiative forcing

Sanz-Morère et al., 2021, state that the radiative effect of clouds overlapping with contrails isn't understood well.[199] For a given contrail, the cloud cover, and the type of cloud cover (thick clouds, low level clouds, cirrus clouds) can dictate whether the contrail is warming, cooling, or if it has a notable radiative impact at all.[200] Sanz-Morère et al. modelled the impact of cloud-contrail overlap on RF and found in their study of 2015 flight data, that roughly 75% of contrail overlapped with clouds, and that including these clouds into calculations increased the global net RF from $0.7mWm^{-2}$ to $9.7mWm^{-2}$, highlighting the importance of this term. In addition, they

[192] Chen, C.C. and Gettelman, A., 2013. Simulated radiative forcing from contrails and contrail cirrus. *Atmospheric Chemistry and Physics*, *13*(24), pp.12525-12536.
[193] Schumann, U., Mayer, B., Graf, K. and Mannstein, H., 2012. A parametric radiative forcing model for contrail cirrus. *Journal of Applied Meteorology and Climatology*, *51*(7), pp.1391-1406.
[194] Schumann, U., Mayer, B., Graf, K. and Mannstein, H., 2012. A parametric radiative forcing model for contrail cirrus. *Journal of Applied Meteorology and Climatology*, *51*(7), pp.1391-1406.
[195] Unterstrasser, S., 2014. Large-eddy simulation study of contrail microphysics and geometry during the vortex phase and consequences on contrail-to-cirrus transition. *Journal of Geophysical Research: Atmospheres*, *119*(12), pp.7537-7555.
[196] Burkhardt, U., Bock, L. and Bier, A., 2018. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. *npj Climate and Atmospheric Science*, *1*(1), p.37.
[197] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, p.117834.
[198] Liou, K.N., Takano, Y., Yue, Q. and Yang, P., 2013. On the radiative forcing of contrail cirrus contaminated by black carbon. *Geophysical Research Letters*, *40*(4), pp.778-784.
[199] Sanz-Morère, I., Eastham, S.D., Allroggen, F., Speth, R.L. and Barrett, S.R., 2021. Impacts of multi-layer overlap on contrail radiative forcing. *Atmospheric Chemistry and Physics*, *21*(3), pp.1649-1681.
[200] Bugliaro, L, 2023, 'Potential and limiations of satellite remote sensing for contrail avoidance', Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc,4:00:00

investigated the radiative impact of contrails overlapping with each other – this was not found to be as significant, with the total RF in their study dropping by just 3% when accounting for this. Further research in this area would be helpful to increase confidence in capturing the effect of contrail-cloud overlap.

Modelling the cloud dehydrating effect on contrail climate impact

Contrails/contrail cirrus compete with natural cirrus for the removal of supersaturated water vapour in the ambient atmosphere to form ice crystals, and, since water vapour more readily condenses on aircraft soot than on other airborne particles (see section on aerosol-cloud interactions), contrails/contrail cirrus tend to reduce natural cirrus cloud cover at flight level, partially offsetting the contrail/contrail cirrus warming effect.[201] Capturing this process is important for estimating the ERF to RF ratio. However, only a small number of global climate models quantify ERF, and the degree of complexity and completeness varies between models.[202] Therefore more work needs to be done to build towards a consensus on this topic.

Investigating the conditions necessary for contrail persistence

It is commonly agreed that ice supersaturation is a prerequisite for contrail persistence. However, recent findings suggest that persistent contrail cirrus occurs more often than expected in slightly subsaturated regions (where the relative humidity with respect to the ice phase, RHice, is around 90%), indicating possible larger contrail cirrus coverage and radiative forcing.[203] [204]

Modelling of the surface temperature impact of contrails

As discussed in section 2, the surface temperature change resulting from contrail ERF may not be the same as CO_2 – further global modelling in this area would be useful to inform discussions around attempts to limit global temperature increase.

Modelling ISSR and cirrus clouds in General Circulation Models

General Circulation Models (GCM) are large computationally expensive models which have been used to estimate global mean contrail RF.[205] They operate with grid cells which can be very large, e.g. Schumann et al., 2015, estimated contrail RF with a grid size of roughly 200km.[206] The representation of cloud microphysics remains a

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201 Bickel, M., Ponater, M., Bock, L., Burkhardt, U. and Reineke, S., 2020. Estimating the effective radative forcing of contrail cirrus. *Journal of Climate*, *33*(5), pp.1991-2005.
202 Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. *Environmental Science: Atmospheres*, *3*(12), pp.1693-1740.
203 Li, Y., Mahnke, C., Rohs, S., Bundke, U., Spelten, N., Dekoutsidis, G., Groß, S., Voigt, C., Schumann, U., Petzold, A. and Krämer, M., 2023. Upper-tropospheric slightly ice-subsaturated regions: frequency of occurrence and statistical evidence for the appearance of contrail cirrus. Atmospheric Chemistry and Physics, 23(3), pp.2251-2271.
204 Petzold, A., Neis, P., Rütimann, M., Rohs, S., Berkes, F., Smit, H.G., Krämer, M., Spelten, N., Spichtinger, P., Nédélec, P. and Wahner, A., 2020. Ice-supersaturated air masses in the northern mid-latitudes from regular in situ observations by passenger aircraft: vertical distribution, seasonality and tropospheric fingerprint. *Atmospheric chemistry and physics*, *20*(13), pp.8157-8179.
205 Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, p.117834.
206 Schumann, U., Penner, J.E., Chen, Y., Zhou, C. and Graf, K., 2015. Dehydration effects from contrails in a coupled contrail–climate model. *Atmospheric Chemistry and Physics*, *15*(19), pp.11179-11199.

challenge for most GCM, mainly due to the variable and inhomogeneous spatial structure of ISSR and ice clouds on sub grid scales.[207], [208, 209, 210, 211] Most GCM's use a saturation adjustment parameterisation which causes unrealistic amounts of water vapour in the UTLS, because they do not allow water vapour levels to go above saturation with respect to ice. As discussed above, the accuracy of weather models to predict cirrus clouds and other low-level clouds is also important for estimating the RF of a contrail. Lastly, not all models include the atmospheric processes (e.g. gravity waves) some argue are necessary to represent ISSR.[212]

Number of contrail models

Low confidence in contrail/contrail cirrus simulations and their RF estimates is also driven by the low number of models currently available[213]. Combining the results of multiple models, a technique called ensemble modelling, can improve the overall prediction accuracy, especially if the individual models in the ensemble are varied.

Summary of research area recommendations on contrail climate impact

Recommended areas for future research are summarised as:

- Improving the representation of contrail properties and processes in contrail models to improve the estimate of global contrail radiative forcing, enabling more informed comparisons to estimates of aviation emitted CO_2 on radiative forcing. This includes radiative transfer modelling and cloud physics modelling.
- Further modelling of the RF impact of a contrail overlapping with other clouds to improve confidence in results already obtained. Further modelling of contrail interaction with natural cirrus, and thus improving the estimate for the RF to ERF ratio. This is perhaps not as critical relative to the other gaps, as Lee et al., 2023, state there is consensus that the ratio is around half.[214]
- Further modelling of the surface temperature change resulting from contrail ERF.

[207]Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, p.117834.
[208] Tan, X., Huang, Y., Diao, M., Bansemer, A., Zondlo, M.A., DiGangi, J.P., Volkamer, R. and Hu, Y., 2016. An assessment of the radiative effects of ice supersaturation based on in situ observations. Geophysical Research Letters, 43(20), pp.11-039.
[209] Diao, M., Zondlo, M.A., Heymsfield, A.J., Avallone, L.M., Paige, M.E., Beaton, S.P., Campos, T. and Rogers, D.C., 2014. Cloud-scale ice-supersaturated regions spatially correlate with high water vapor heterogeneities. *Atmospheric Chemistry and Physics*, *14*(5), pp.2639-2656.
[210] Carlin, B., Fu, Q., Lohmann, U., Mace, G.G., Sassen, K. and Comstock, J.M., 2002. High-cloud horizontal inhomogeneity and solar albedo bias. *Journal of climate*, *15*(17), pp.2321-2339.
[211] Pomroy, H.R. and Illingworth, A.J., 2000. Ice cloud inhomogeneity: Quantifying bias in emissivity from radar observations. *Geophysical research letters*, *27*(14), pp.2101-2104.
[212] Podglajen, A., Plougonven, R., Hertzog, A. and Jensen, E., 2018. Impact of gravity waves on the motion and distribution of atmospheric ice particles. *Atmospheric Chemistry and Physics*, *18*(14), pp.10799-10823.
[213] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.
[214] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.

6.2.2 Knowledge gaps surrounding observations

Observations here refers to all measurements of physical quantities relevant to contrails. One category of observations are measurements of contrails themselves: these are very important for guiding model development and verifying simulations. Observations are available from many resources, including satellite imagery and lidar, in flight measurement campaigns, radiosondes (weather balloons), in flight measurements (for example the IAGOS, In-service Aircraft for a Global Observing System,[215] program), ground-based cameras and lidar.

Another important category is the measurements of water vapour in the atmosphere – this improves the accuracy of weather forecasts of ISSR's in the atmosphere. Measurements are available from weather balloons (radiosondes) and sensors carried by commercial aircraft.

ISSR prediction

Observational data of upper tropospheric moisture is crucial for the evaluation and validation of ISSR prediction. However, water vapour remains one of the most challenging parameters of the atmosphere to measure precisely, mainly due to its considerable spatiotemporal variability. In the upper troposphere/lower stratosphere (UTLS) more specifically, water vapour is present only in very low concentrations which are often within range of instrument calibration/uncertainty. Measurements of atmospheric humidity recorded and shared in real time can be fed into weather modelling to improve the accuracy of forecasts.

Important for contrail mitigation is the detection of ice supersaturated regions, ISSR's. ISSR are rare, patchy, and thin/shallow (typically a few hundreds of metres in depth), which makes them difficult to record.

Satellite imagery

Satellites provide a valuable source of live information which can be used in mitigation contexts as well as broader research. Two main types of satellites in the context of contrail detection are geostationary satellites, and polar orbiting satellites. Polar orbiting satellites have a high spatial resolution for observing contrails, but suffer a low temporal resolution, whilst geostationary satellites have a worse spatial resolution but a better temporal resolution.[216] The spatial resolution impacts whether contrails can be seen or not.[217]

Artificial intelligence (AI) can be employed to identify contrails from satellite imagery – considerable work has been done by Google and MIT in this field, and MIT uses satellite contrail detection in their Nowcasting contrail mitigation approach (see section 4.3). One challenge faced by detection algorithms is differentiating contrail

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[215] https://www.iagos.org/

[216] Bugliaro, L, 2023, 'Potential and limiations of satellite remote sensing for contrail avoidance', Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc,4:00:00

[217] Ibid

cirrus from natural cirrus – Bugliaro, 2023, noted that whilst this task was not possible for non-AI convolution algorithms, that AI algorithms are learning to detect contrails which have lost their initial linear shape.[218] Satellite images struggle to detect contrails above thick clouds, however this is not an issue as thick clouds remove the radiative impact of the contrails.[219]

In order to employ AI algorithms, large labelling campaigns are required to train models to identify contrails – this has been done in the US by Google and MIT but not in Europe.[220] Google have made publicly available a labelled contrail dataset (called OpenContrails) which can be used to train contrail detection algorithms.[221] At the Eurocontrol Sustainable Skies Conference, Eurocontrol called for the creation of ContrailNet, a network of industry stakeholders working to bring together European research, with the aim to build up a large and shared repository of contrail observational data.[222] The initial task will then be running labelling campaigns on satellite, ground camera and lidar data to enable the development of contrail detection algorithms. There are perhaps opportunities for UK stakeholders to join this project. Furthermore, it highlights an appetite in the industry to further research efforts in AI and satellite data.

Ground cameras

Jarry and Verry, 2023, highlighted the potential for ground cameras to supplement satellite imagery in contrail detection.[223] They pointed out that they can detect young contrails which satellites are not able to due to resolution limitations. An area for future research is the fusion of these two sources of data, as well as identifying which contrails are missed by ground-based cameras and satellites respectively.[224] Finally, they noted that infrared cameras have the potential to measure contrail physical properties - this could support contrail model development and evaluation.

Summary of research recommendations on contrail and atmospheric water vapour observations

Recommended areas for possible future research include:

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[218] Bugliaro, L, 2023, ‘Potential and limiations of satellite remote sensing for contrail avoidance’, Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc,4:00:00
[219] Bugliaro, L, 2023, ‘Potential and limiations of satellite remote sensing for contrail avoidance’, Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc,4:00:00
[220] Jarry, L, and Very, P, 2023, ‘Contrail Research: The Critical Role of Observational Data & AI’, Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc,3:44:12
[221] Ng, J.Y.H., McCloskey, K., Cui, J., Meijer, V.R., Brand, E., Sarna, A., Goyal, N., Van Arsdale, C. and Geraedts, S., 2023. Opencontrails: Benchmarking contrail detection on goes-16 abi. arXiv preprint arXiv:2304.02122.,
Vancouver,

[222] Jarry, L, and Very, P, 2023, ‘Contrail Research: The Critical Role of Observational Data & AI’, Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc,3:44:12
[223] Jarry, L, and Very, P, 2023, ‘Contrail Research: The Critical Role of Observational Data & AI’, Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc,3:44:12
[224] ibid

- Increasing the amount of observational data of contrails, including its optical depth, ice crystal number and ice crystal size throughout a contrail's lifetime. This may involve more in-flight measuring experiments.
- Obtaining more and higher resolution measurements of water vapour in the atmosphere to help the accuracy of weather forecasts. Measurements recorded and shared in real-time can be used in data assimilation on weather models. Data assimilation is the process of feeding observations into weather models to improve forecast accuracy.
- Exploring the potential to join other European efforts in ContrailNet developing contrail detection algorithms by analysing satellite observational data.
- Bringing together and comparing satellite and ground camera contrail data.

6.2.3 Knowledge gaps surrounding contrail mitigation strategies

Whilst many mitigation modalities have been explored and trialled in different contexts, there remain several areas where future research could usefully be conducted to generate a fuller understanding of the impact and feasibility of various mitigation methods.

Table 9: Examples of knowledge gaps in contrail mitigation strategies

Mitigation strategy	Gap
Navigational contrail avoidance	Difficulties tracking water vapour in the atmosphere. Off the shelf forecast model data underestimates frequency and degree of ISSR. More research in understanding properties of contrail cirrus in slightly subsaturated regions of the atmosphere. Overall climate impact when considering increased CO_2 impacts due to change of flight paths.
SAF	Uncertainty around the impact of SAF on non-CO_2 impacts. The impact on aerosol-cloud and contrails should both be modelled due to the coupled impact of soot.
Combustion design or hydrotreating fuel	Like SAF the impact on aerosol-cloud and contrails should both be modelled due to the coupled impact of soot. Understanding of the trade-off between NOx and soot Further research to understand the benefits of elastomer technologies. Complete understanding of the overall CO_2 and non-CO_2 impact due to emissions at the refinery.

Navigational contrail avoidance

Three main research gaps are highlighted in this section followed by a summary of a recent contrail avoidance flight trial and a list of research suggestions which stemmed from this.

Firstly, navigational contrail avoidance strategies which utilise weather forecasts of ISSR's are subject to uncertainties due to the difficulties of tracking water vapour in the atmosphere. Simulations of contrail development for example in CoCiP/pycontrails depend on these weather forecasts. The NWP models (Numerical Weather Prediction models) used for these forecasts operate with a grid system, and track the flux of variables over grid cells, as well as parameterising processes which take place over smaller distances, below the resolution of the grid. Whilst NWP models are good at predicting temperature and pressure in the atmosphere, water vapour is more challenging.

NWP model's capability to reproduce observed statistics of ISSR is limited, with current off-the-shelf forecast model data underestimating the frequency and degree of ISSR.[225] [226] [227] [228] This poses challenges in making accurate predictions of persistent contrails on the time and space scales required for operational implementation of navigational contrail avoidance on an individual flight basis as a mitigation measure.

Secondly, Li et al., 2023, found that contrail cirrus may persist in slightly subsaturated regions (regions close to, but not quite cool or wet enough to be an ISSR).[229] They suggested that the threshold of RHice (relative humidity with respect to ice, a function of water vapour and temperature) leading to aircraft re-routing in a navigational mitigation strategy using NWP forecasts, may need to be lowered. The authors requested further research to be done in estimating the properties of contrail cirrus in these slightly subsaturated regions of the atmosphere.

Thirdly, there are concerns about a potential increase in fuel burn and therefore CO_2 emissions from changing flight levels or route, although this particular concern has been challenged by recent studies. [230] [231] [232] Whilst the former two points were

[225] Agarwal, A., Meijer, V.R., Eastham, S.D., Speth, R.L. and Barrett, S.R., 2022. Reanalysis-driven simulations may overestimate persistent contrail formation by 100%–250%. *Environmental Research Letters*, *17*(1), p.014045.
[226] Reutter, P., Neis, P., Rohs, S. and Sauvage, B., 2020. Ice supersaturated regions: properties and validation of ERA-Interim reanalysis with IAGOS in situ water vapour measurements. *Atmospheric chemistry and physics*, *20*(2), pp.787-804.
[227] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. *Environmental Science: Atmospheres*, *3*(12), pp.1693-1740.
[228] Gierens, K., Matthes, S. and Rohs, S., 2020. How well can persistent contrails be predicted?. *Aerospace*, *7*(12), p.169.
[229] Li, Y., Mahnke, C., Rohs, S., Bundke, U., Spelten, N., Dekoutsidis, G., Groß, S., Voigt, C., Schumann, U., Petzold, A. and Krämer, M., 2023. Upper-tropospheric slightly ice-subsaturated regions: frequency of occurrence and statistical evidence for the appearance of contrail cirrus. *Atmospheric chemistry and physics*, *23*(3), pp.2251-2271.
[230] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. *Environmental Science: Atmospheres*, *3*(12), pp.1693-1740.
[231] Avila, D., Sherry, L. and Thompson, T., 2019. Reducing global warming by airline contrail avoidance: A case study of annual benefits for the contiguous United States. *Transportation Research Interdisciplinary Perspectives*, *2*, p.100033.
[232] Roosenbrand, E., Sun, J. and Hoekstra, J., 2023. Contrail minimization through altitude diversions: A feasibility study leveraging global data. *Transportation Research Interdisciplinary Perspectives*, *22*, p.100953.

specific to strategies using weather forecasts, this challenge applies to satellite-based decision making. An increase in fuel burn means that the decision to divert a flight will depend on the metric used to quantify and compare contrail versus CO_2 climate impacts. As Lee *et al.*, 2023, report, "even if the forcing of the time- and location-specific avoided contrail was known, any gain would depend on the metric chosen to compare contrail and CO_2 climate impacts. For metrics such as the GWP or GTP, use of a longer time horizon would in general make it harder to justify diversion."[233]

An Air Traffic Control contrail avoidance trial in Northern Europe in 2021 concluded, with caveats due to uncertainties, that "avoiding persistent contrails is possible on average."[234] The trial ran for 264 days, and data was collected on when contrails were predicted, or not, and when they were observed, or not. There were 23 cases when contrails were predicted to form along the original flight path, and when the aircraft was subsequently deviated.

The authors of the study noted that the ratio of persistent contrails not being observed to persistent contrails being observed (when the model predicted contrails), was much higher on the days that aircraft were deviated than not: 3.6 against 1.2. The authors viewed this as evidence that it is possible to avoid persistent contrails through deviations and suggested further areas of work to understand the impact and approach better, notably:

- Taking more measurements of upper-troposphere humidity to feed into forecasts.
- Improving satellite observations and improving algorithms and software to retrieve data about persistent contrails from those observations.
- Supplementing satellite data with ground observations.
- Supporting traffic re-routing with numerical algorithms.

The use of SAF to reduce contrail the radiative impact of contrails

Whilst the availability of SAF today, and for likely more than a decade, is limited, there have been a number of flight trials investigating the impact of SAF on contrails – see section 4.3.[235] SAF has the potential to impact contrails as its use reduces the number of soot particles, which, for conventional fuel carrying engines, become the cores of contrail ice crystals. It is unclear whether the use of SAF results in reductions in contrail cirrus forcing, as modelling results are conflicting.

[233] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.
[234] Sausen, R., Hofer, S.M., Gierens, K.M., Bugliaro Goggia, L., Ehrmanntraut, R., Sitova, I., Walczak, K., Burridge-Diesing, A., Bowman, M. and Miller, N., 2023. Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world?. *Meteorologische Zeitschrift*.
[235] Klöwer, M., Allen, M.R., Lee, D.S., Proud, S.R., Gallagher, L. and Skowron, A., 2021. Quantifying aviation's contribution to global warming. Environmental Research Letters, 16(10), p.104027.

Lee et al., 2023, presented recent findings on the effect of SAF on ice nucleation and radiative forcing which demonstrate some of the uncertainty around SAF.[236] The findings included the following:

- The amount of soot appears to be dependent on the aromatic content of the fuel – pure SAF has a much less aromatic content than Kerosene. Measurements have shown the reduction in soot from using SAF compared to Kerosene.
- Measurements have been taken showing that SAF/fossil fuel blends result in reduced ice crystal concentrations.[237] This confirmed earlier theoretical studies (see references within Lee et al), and gives support to investigating the "potential outcome and co-benefit of reducing CO_2 and potentially contrail forcing with increased usages of SAF".[238] [239]
- However, theoretical modelling has suggested that as soot emissions reduce there is a possibility for an increase in ice nucleation.[240]

The following is a more in-depth assessment of the effect of using SAF on contrails, again using the summary provided in Lee et al., 2023.

In their global simulation, which importantly assumed a linear relationship between soot and the number of ice crystals (and therefore only applies in the soot rich regime – further details given below), Burkhardt *et al*., 2018, found that the radiative forcing decreased as the soot particle number decreased (roughly -50% when soot numbers dropped 80%).[241] A more complex simulation, Bier and Burkhardt, 2022, got a change of -41% RF with an 80% drop in soot.[242] However, in a separate study, Caiazzo et al., 2017, modelled low-soot biofuels and found that with 67-75% drops in soot number lead to an RF change of -4 to +18% depending on what ice crystal geometry was used in the model.[243]

Lee et al., 2023, do not draw firm conclusions from this. They state that due to the low number of global climate models incorporating contrails, "the modelling reductions in RF from reduced soot number emissions from usage of SAF described by Burkhardt et al. (2018) and Bier & Burkhardt (2022) should be interpreted as indicative only, and subject to change, should more models and calculations become

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[236] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.

[237] Voigt, C., Kleine, J., Sauer, D., Moore, R.H., Bräuer, T., Le Clercq, P., Kaufmann, S., Scheibe, M., Jurkat-Witschas, T., Aigner, M. and Bauder, U., 2021. Cleaner burning aviation fuels can reduce contrail cloudiness. Communications Earth & Environment, 2(1), p.114.

[238] Burkhardt, U., Bock, L. and Bier, A., 2018. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. *npj Climate and Atmospheric Science*, *1*(1), p.37.

[239] Bier, A. and Burkhardt, U., 2019. Variability in contrail ice nucleation and its dependence on soot number emissions. *Journal of Geophysical Research: Atmospheres*, *124*(6), pp.3384-3400.

[240] Kärcher, B., 2018. Formation and radiative forcing of contrail cirrus. *Nature communications*, *9*(1), p.1824.

[241] Burkhardt, U., Bock, L. and Bier, A., 2018. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. *npj Climate and Atmospheric Science*, *1*(1), p.37.

[242] Bier, A. and Burkhardt, U., 2022. Impact of parametrizing microphysical processes in the jet and vortex phase on contrail cirrus properties and radiative forcing. *Journal of Geophysical Research: Atmospheres*, *127*(23), p.e2022JD036677.

[243] Caiazzo, F., Agarwal, A., Speth, R.L. and Barrett, S.R., 2017. Impact of biofuels on contrail warming. Environmental Research Letters, 12(11), p.114013.

available.” The results are only applicable for the soot rich regime ($> 10^{14}$ particles per kg fuel).[244] They summarise that the positive impact on SAF on contrail ERF “should be interpreted as tentative and as yet unproven”. Reducing uncertainty around the impact of using SAF is therefore an area for further research.

Finally, the use of SAF will impact the aerosol-radiation and aerosol-cloud interactions. It would reduce sulfur emissions (Lee et al., 2023), which as described in section 2 are thought to contribute to negative forcing. SAF would also reduce soot-cloud interactions (see section 2) which could result in positive or negative cooling. It is recommended by Lee et al 2023 that when modelling contrails that the aerosol-cloud interactions should be modelled too due to the coupled impact of the soot.

Reducing soot emissions through combustion design or through hydrotreating fuel to reduce the radiative impact of contrails.

By a similar mechanism described for SAF, reducing soot emissions through either combustion design or hydrotreating fuel may reduce the radiative forcing of contrails.

Teoh et al., 2020, found in their computational study of mitigating contrail warming in Japanese airspace that the result of setting all modelled flights to have a double annular combustor vs a single annular combustor (with the former having reduced soot emissions compared to the latter) was a 68.8% drop in contrail energy forcing.[245] The same uncertainty as for SAF arises when operating with very low soot emission values – the number of ice crystals may eventually increase as the number of soot particles drops. However low soot combustors may not have such low soot emissions as to encounter this problem. A key point noted by Lee et al., 2023, is that for “some combustor technologies there is an inherent trade-off between the conditions to reduce NOx and soot”. [246]

Similarly reducing aromatic content of hydrocarbon fuels by actively removing them (e.g., hydrotreating) present a number of challenges that require further consideration, including:

- Increased CO_2 emission at the fuel refinery operation: Lee et al., 2023, citing Faber et al., 2022, reported that decreasing the aromatic content of kerosene requires 97 kg of CO_2 emissions per tonne of kerosene.[247] [248]

[244] See Kärcher, 2018, for more details – the soot rich regime refers to the modelling results that for high soot emissions, there is a linear trend between number of ice crystals and soot emissions. However, when soot emissions are very low (ie out of the soot-rich regime) this trend no longer holds, and the number of ice crystals rises again, due to nucleation occurring on aqueous ultrafine aerosols (Lee et al., 2023).
Kärcher, B., 2018. Formation and radiative forcing of contrail cirrus. *Nature communications*, *9*(1), p.1824.
[245] Teoh, R., Schumann, U., Majumdar, A. and Stettler, M.E., 2020. Mitigating the climate forcing of aircraft contrails by small-scale diversions and technology adoption. Environmental Science & Technology, 54(5), pp.2941-2950.
[246] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.
[247] Faber, J., Király, J., Lee, D., Owen, B. and O’Leary, A., 2022. Potential for reducing aviation non-CO2 emissions through cleaner jet fuel. *CE-Del*, *22*, p.022.
[248] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.

- Elastomer technologies for fuel systems (this challenge also applies when using SAF): Lee et al., 2023, recommended the research of elastomers, a type of material used in fuel systems, which are not dependent on the level of aromatics to be able to form seals within fuel systems.[249]

Finally, Lee et al., 2023, note that due to the uncertainty surrounding soot-cloud interactions, if mitigation attempts are made to reduce the soot emissions, the net climate outcome is unknown.[250] This applies to hydrotreating fuels, combustor technologies and the use of SAF.

Summary of research area recommendations on contrail mitigation strategies

Recommendations for future research include:

- Improving the representation of ISSR in numerical weather prediction models.
- Investigating the properties of contrails in subsaturated regions of the atmosphere.
- Further assessing fuel burn penalties for contrail avoidance.
- Investigating and modelling how air traffic management may be conducted when many flights are looking to avoid ISSR areas, and the resulting fuel burn penalty.
- Developing more and higher accuracy models to investigate the impact of low soot emissions (produced either from SAF, hydrotreated fuels or low soot combustors) on contrail properties and radiative forcing.

6.2.4 Knowledge gaps around future NOx impacts

At the fundamental level, improved modelling of the transition from the aircraft plume through to the scale of the global models would provide better estimates of the chemical impact of aircraft emissions at larger scales. Chemical uncertainties in the atmospheric models are assessed through on-going model comparison exercises and it is important to assess these results for reactions or other processes which are particularly important for estimating the impact of NO_x emissions from aviation. Ensuring integration with parallel research programmes on air quality from ground level (which will include take-off and landing emissions) NOx is important.

More model studies estimating ERF as well as RF would be valuable (a) in increasing confidence in the limited results to date and (b) to improve understanding of the relative importance of the short term O_3 and the methane lifetime components of the NO_x impacts. At the same time, studies of the spatial and temporal influences on the NO_x impacts should be carried out and the sensitivity of these impacts to a

[249] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.

[250] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.

changing background atmosphere.[251] These are especially important as we enter a period of expected changing in emissions of many important constituents including methane.

6.2.5 Knowledge gaps around aerosol-cloud interactions

As in chapter 3, the aerosol-cloud interactions considered in this review are sulfate-cloud and soot-cloud interactions. Lee et al., 2021, noted that sulfate-cloud RF estimates were a strong function of how sensitive a modelled cloud's radiative forcing is to changes in the number of aerosols, which in turn depends on "uncertain model processes".[252] Further research reducing uncertainty and constraining estimates of the sulfate-cloud interaction RF are required.

There have been many modelling studies estimating the radiative impact resulting from soot interacting with clouds. The modelled RF has varied significantly, including large negative forcings of 100s of mWm^{-2}. However, in recent years it appears to have moved towards lower values[253]. There remains disagreement in the academic community on how to model certain processes. Further research is required to reduce the uncertainty around the modelled RF impact. Suggestions for future research include:

- Sulfur-cloud: reducing the uncertainties in the sulphate / liquid cloud drop interactions and the consequent radiative impact through measurements and modelling.
- Soot-cloud: reducing the uncertainties in RF estimates, through avenues including the further analysis of the physical mechanisms which affect the ability of soot particles to nucleate ice crystals and thus impact cirrus clouds. Additionally improving global modelling representations of vertical updraft velocities will also help capture the impact of soot particles.

6.2.6 Stakeholder workshop insights

Most of the additional gaps highlighted by stakeholders were around understanding the value of the impacts, easy to use methods and metrics and comparison between non-CO_2 and CO_2 impacts to enable the delivery, and measurement of mitigations, with operational constraints and validation emerging as critical areas.

Stakeholders highlighted the need for independent validation tools to ensure data accuracy, particularly concerning contrails and weather forecast data. This included a call for improved global satellite (and potentially high-altitude drone-based) validation and green light trials aimed to gather empirical evidence to persuade

[251] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.
[252] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834
[253] Testa, B., Durdina, L., Alpert, P.A., Mahrt, F., Dreimol, C.H., Edebeli, J., Spirig, C., Decker, Z.C., Anet, J. and Kanji, Z.A., 2023. Soot aerosol from commercial aviation engines are poor ice nucleating particles at cirrus cloud temperatures. EGUsphere, 2023, pp.1-47.

stakeholders about the tangible positive outcomes achievable through emission reduction strategies. Stakeholders also considered the need for the required data to inform the Minimum Viable Product of a monitoring and reporting framework.

Part of the approach to managing contrails requires an appreciation on the timeline of lifetime warning from contrails. Understanding that the heating effect (warming / cooling) from contrails dissipates after the cirrus cloud dissipates. However, the needs to be a consideration on the timeline and what decision-makers need to target.

Government intervention was deemed pivotal, stressing the necessity for holistic guidance, clear parameters, and aligned incentives to catalyse emission reduction. Early policy interventions, especially in advancing airspace complexities and incentivising key investments, were highlighted as critical steps.

Communication and strategy development emerged as key facilitators. Establishing a common language among stakeholders for effective communication and adopting counterfactual analysis for better decision-making were underscored as imperative.

Future focus areas revolved around the scalability of contrail management and technological advancements. The debate over contrail management's scalability highlighted the need for nuanced approaches to address localised inefficiencies. Moreover, emphasis was placed on technological advancements, particularly in aircraft instrumentation, and collaboration with meteorological offices to enhance data accuracy and advance emission reduction strategies.

At the fundamental level, improved of the transition from the aircraft plume through to the scale of the global models would provide better estimates of the chemical impact of aircraft emissions at larger scales. Chemical uncertainties in the atmospheric models are assessed through on-going model comparison exercises and it is important to assess these results for reactions or other processes which are particularly important for estimating the impact of NOx emissions from aviation. Ensuring integration with parallel research programmes on air quality from ground level NOx is important.

6.3 Conclusion

Whilst a significant number of knowledge gaps have been identified in the literature, surrounding contrail climate impact, contrail and water vapour observations, contrail mitigation strategies, and future NOx impacts, promising signs of potential have been noted too. For example Sausen et al., 2023, reporting a potentially successful contrail deviation trial in 2021, and Bier & Burkhardt, 2022, obtaining lower radiative forcing when reducing soot emissions in their model.[254] [255] More measurements of

[254] Sausen, R., Hofer, S.M., Gierens, K.M., Bugliaro Goggia, L., Ehrmanntraut, R., Sitova, I., Walczak, K., Burridge-Diesing, A., Bowman, M. and Miller, N., 2023. Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world?. Meteorologische Zeitschrift.

[255] Bier, A. and Burkhardt, U., 2022. Impact of parametrizing microphysical processes in the jet and vortex phase on contrail cirrus properties and radiative forcing. *Journal of Geophysical Research: Atmospheres*, *127*(23), p.e2022JD036677.

water vapour in the atmosphere shared in real-time for use in weather forecasts would likely help to improve ISSR prediction accuracy. There is appetite in the industry to develop more contrail detection AI algorithms. More modelling of the ERF of contrails would be beneficial too (since this has not been done by many models yet).[256] More modelling of the NOx impacts would help increase confidence in defining the size and therefore importance of its climate effect. Further modelling may also improve understanding of the sensitivity of NOx impacts to both potential changes in flight patterns (resulting from contrail-cirrus mitigation strategies) and to possible changes in the chemical composition of the future atmosphere. Whilst the radiative impact of aerosol-cloud interactions remain highly uncertain, recent estimates for soot-cloud interactions are smaller than those made previously[257] and there has been extensive work in the literature recently relevant to the subject. Continued work on representing vertical wind velocities in global models, which are very important in cirrus cloud processes, will aid in producing a best estimate for the forcing.[258] A summary of the future research areas is included in Table 10 on the next page.

[256] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.
[257] Testa, B., Durdina, L., Alpert, P.A., Mahrt, F., Dreimol, C.H., Edebeli, J., Spirig, C., Decker, Z.C., Anet, J. and Kanji, Z.A., 2023. Soot aerosol from commercial aviation engines are poor ice nucleating particles at cirrus cloud temperatures. EGUsphere, 2023, pp.1-47.
[258] Righi, M., Hendricks, J. and Beer, C.G., 2021. Exploring the uncertainties in the aviation soot–cirrus effect. *Atmospheric Chemistry and Physics*, *21*(23), pp.17267-17289.

Table 10: Future research areas.

Section	Future research areas
Climate impact of contrails	Improved/new modelling on: - Contrail cloud physics and radiative processes - Cloud overlap on contrail radiative forcing - Cloud dehydrating effect on contrail climate impact - Surface temperature impact of contrails - ISSR and cirrus clouds in General Circulations Models - Increase in number of contrail models. Investigations into the conditions necessary for contrail persistence
Observations	Increase the amount of observational data on contrails including: - More in-flight measuring experiments - More and higher resolution of water vapour in the atmosphere - Improved satellite imagery enhanced by the use of AI to identify contrails Data assimilation to improve forecast accuracy - Comparisons of satellite and ground camera contrail data.
Contrail mitigations	Further research into navigational contrail avoidance including o Overall climate impact when considering increased CO_2 impacts due to change of flight paths. Decrease the uncertainty around the impact of SAF and combustion design on non-CO_2 impacts by modelling both aerosol cloud and contrails impacts. Further research into the trade-off between NOx and soot, as well as CO_2 in combustion design.
NOx impacts	Improved modelling of the transition from the aircraft plume to global models to provide better estimates. Ensure integration with parallel research programmes on air quality from ground level (which will include take-off and landing emissions). Better modelling to estimate the ERF and RF values and to understand the relative importance of the short term O_3 and the methane lifetime components of the NOx impacts.
Aerosol-cloud interaction	Further research to reduce uncertainty and constrain the estimates of impact for sulfur-cloud and soot-cloud. Further analysis of the mechanisms which affect the ability for soot particles to nucleate ice crystals and therefore impact cirrus clouds.

7 Previous, current and upcoming international research projects and programmes exploring non-CO_2 impacts

7.1 Introduction

This section presents a list of recent international research programmes and projects from academia and industry which are focused on the non-CO_2 impacts of aviation. It discusses relevant research areas identified by stakeholders and provides insights into potential gaps and opportunities for resource allocation. The projects are categorised into five broad groups:

1. **Trajectory Optimisation and Air Traffic Management (ATM):** Projects in this category focus on optimising flight trajectories and ATM procedures to reduce non-CO_2 impacts, such as contrail formation and NOx emissions.
2. **Contrail Prediction Tools:** These projects aim to develop and improve models and tools for predicting contrail formation and their climate impact.
3. **Combustor and Aircraft Design:** Projects in this category investigate design modifications and technologies to reduce NOx emissions and improve fuel efficiency.
4. **Sustainable Aviation Fuel (SAF):** These projects explore the production, use, and impact of SAF as a means to reduce non-CO_2 impacts from aviation.
5. **Non-CO_2 impacts:** Projects in this category assess the climate and environmental non-CO_2 impacts from aviation, including contrails, NOx, and water vapour.

Each category includes a summary table of projects, with one project discussed in more detail as an example.

Alongside this, as previously highlighted in section 2.1 and therefore not referenced in this Chapter, DfT, alongside NERC and DBT have launched a non-CO_2 research programme to better understand aviation's non-CO_2 impacts and potential mitigations. The Programme has two streams, one to fund academic-led research and one to fund industry-led research, though partnerships between the two are encouraged. The programme will run until 2028. The first academic call was launched in October 2023, and 10 projects have been selected to receive funding. The industry call for projects was launched in May 2024.

7.2 Trajectory optimisation and air traffic management

Minimising the contrail climate impact by flight altitude deviations is a commonly suggested approach. Google (which is leading an operational trial with a selection of airlines, discussed below) cites a paper authored by researchers at Imperial College and DLR, which modelled the impact of altitude deviations on contrail forcing.[259,] This shows the impact of UK research in this sphere as well as the impact of academia on industry.

Both research into mitigation approaches and the development of operational platforms has been conducted (e.g., ClimOP and the ‘Contrail avoidance decision support and evaluation’ project led by MIT) and flight trials have already been undertaken: for example, Google working with American Airlines, SATAVIA with Etihad Airways and 12 other operators in trials supported by the European and UK Space Agencies, MIT with Delta Airlines (ongoing), and the Maastricht Upper Area Control Centre (MUAC) contrail prevention trial.[260] [261] [262] [263] [264] [265] These flight trials have involved different approaches: in the case of SATAVIA these were pre-tactical,[266] in the MIT and Delta Airlines trial these are tactical deviations[267] undertaken using Nowcasting (see below) with suggested deviations sent to the cockpit.[268] Deviations in the MUAC trial were also tactical. The approaches use different technologies: SATAVIA uses forecasting generated via numerical weather prediction modelling, whilst MIT is using satellite data to inform decision making off the back of observed contrails (Nowcasting).

Molloy *et al*., 2022, presented pros and cons for both pre-tactical and tactical approaches: pre-tactical interventions reduce workload of air traffic controllers and pilots, however as forecasts may differ when the flight is flown against when the flight plan was filed, rerouting may not be effective for contrail mitigation.[269] In comparison, tactical interventions allow for the most up to date contrail relevant data to be used whilst also having up to date flight parameters (e.g. departure time). This said, recommendations for deviations may not always be accepted depending on other factors such as traffic levels.

Optimising flight trajectories to reduce non-CO_2 impacts whilst accounting for a potential increase in CO_2 remains a key area of research. The EU funded CICONIA project will research different ATM approaches to reduce the effect of contrails,

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[259] Teoh, R., Schumann, U., Majumdar, A. and Stettler, M.E., 2020. Mitigating the climate forcing of aircraft contrails by small-scale diversions and technology adoption. Environmental Science & Technology, 54(5), pp.2941-2950.
[260] European Commission. (2024). CLIMATE ASSESSMENT OF INNOVATIVE MITIGATION STRATEGIES TOWARDS OPERATIONAL IMPROVEMENTS IN AVIATION. Available at: https://cordis.europa.eu/project/id/875503
[261] Ascent. (2021). CONTRAIL AVOIDANCE DECISION SUPPORT AND EVALUATION. Available at: https://ascent.aero/project/contrail-avoidance-decision-support-and-evaluation/
[262] Google Research. (n.d). Project Contrails. Available at: https://sites.research.google/contrails/
[263] Etihad. (2022). Etihad Airways performs 42 EcoFlights including 22 contrail flights over five days. Available at: https://www.etihad.com/en-gb/news/etihad-airways-performs-42-ecoflights-including-22-contrail-flights-over-five-days
[264] Barrett, S, 2023, ‘Observational contrail avoidance’, Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc&t=7841s, 1:57:20
[265] Sausen, R., Hofer, S.M., Gierens, K.M., Bugliaro Goggia, L., Ehrmanntraut, R., Sitova, I., Walczak, K., Burridge-Diesing, A., Bowman, M. and Miller, N., 2023. Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world?. *Meteorologische Zeitschrift*.
[266] Deviations are suggested to the crew prior to the flight.
[267] Deviations are not planned prior to the flight.
[268] Barrett, S, 2023, ‘Observational contrail avoidance’, Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc&t=7841s, 1:57:20
[269] Molloy, J., Teoh, R., Harty, S., Koudis, G., Schumann, U., Poll, I. and Stettler, M.E., 2022. Design principles for a contrail-minimizing trial in the north atlantic. *Aerospace*, *9*(7), p.375.

whilst CONCERTO, another EU project, focussed on trajectory optimisation, will study how to maximise CO_2 reduction in emissions, whilst also managing non-CO_2.[270,271] The project appears to be looking to aid mitigation approaches in the near term as it seeks to find solutions which can integrate with current ATM setups without major changes.

There are several voices in the industry which feel that mitigation should wait before uncertainties are reduced.[272] Table 11, on the next page, and subsequent prose discusses further research that is being undertaken around trajectory optimization and Air Traffic Management.

[270] European Commission. (2023). Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment. Available at: https://cordis.europa.eu/project/id/101114613
[271] European Commission. (2023). dynamic cOllaboration to geNerlaize eCo-friEndly tRajecTOries, Available at: https://cordis.europa.eu/project/id/101114785
[272] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.

Table 11: Summary of industry & government projects on Trajectory Optimisation and Air Traffic Management

Project	Years	Key themes	Lead	Funders	Funding amount
Climate effects reduced by Innovative Concept of Operations – Needs and Impacts Assessment (CICONIA)[273]	2023-2026	Operations guidance, weather forecasting	Airbus	EU	Total: £7.4m EU: £4.2m
dynamicC cOllaboration to geNeralize eCo-friEndly tRajectTOries (CONCERTO)[274]	2023-2026	Eco-friendly trajectories	Thales	EU	Total: £7.2m EU: £4.0m
ClimOP[275]	2020-2023	Mitigation approach analysis	Deep Blue SRL	EU	£2.56m
Contrail avoidance decision support and evaluation[276,277]	2021-	Satellite data, Nowcasting, vertical deviations	MIT	US	US: £0.87m, matched by stakeholders
FlyATM4E[278]	2020-2022	Climate-optimised aircraft routes	DLR	EU	£0.85m
MUAC Contrail trial[279]	2021	Mitigation trial, tactical	Eurocontrol		
Project Contrails[280]	2023	Satellite data, Mitigation trial	Google		
MIT & Delta Contrail avoidance project[281]	Current	Mitigation trial, nowcasting	MIT		
Satavia	2023	Mitigation trial, pre-tactical	Satavia, Icelandair, others	ESA/UK SA	

[273] European Commission (2023). Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment. Available at: https://cordis.europa.eu/project/id/101114613
[274] European Commission. (2023). dynamic cOllaboration to geNerlaize eCo-friEndly tRajecTOries, Available at: https://cordis.europa.eu/project/id/101114785
[275] European Commission. (2024). CLIMATE ASSESSMENT OF INNOVATIVE MITIGATION STRATEGIES TOWARDS OPERATIONAL IMPROVEMENTS IN AVIATION. Available at: https://cordis.europa.eu/project/id/875503
[276] Ascent. (2021). CONTRAIL AVOIDANCE DECISION SUPPORT AND EVALUATION. Available at: https://ascent.aero/project/contrail-avoidance-decision-support-and-evaluation/
[277] Ascent. (n.d). Project 078 Contrail Avoidance Decision Support and Evaluation, Available at: https://s3.wp.wsu.edu/uploads/sites/2479/2023/06/ASCENT-Project-078-2022-Annual-Report.pdf
[278] European Commission. (n.d.). Flying Air Traffic Management for the benefit of environment and climate. Available at: https://cordis.europa.eu/project/id/891317
[279] Sausen, R., Hofer, S.M., Gierens, K.M., Bugliaro Goggia, L., Ehrmanntraut, R., Sitova, I., Walczak, K., Burridge-Diesing, A., Bowman, M. and Miller, N., 2023. Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world?. *Meteorologische Zeitschrift*.
[280] Google Research. (n.d). Project Contrails. Available at: https://sites.research.google/contrails/
[281] Barrett, S, 2023, 'Observational contrail avoidance', Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc&t=7841s, 1:57:20

Example project

CICONIA (Climate effects reduced by Innovative Concept of Operation – Needs and Impacts Assessment), 2023-2026[282]

'CICONIA's ambition is to improve the understanding of non-CO2 impacts with regards to the current aircraft/engine technologies and operating fleet, as well as their evolution and their climate effects, but with a clear objective to evaluate and develop impact reduction solutions covering several promising mitigation options on flight operations'. This project is Coordinated by Airbus (France). The four main topics are:

1) The development of a weather service to be used to aid mitigation through improving weather forecasting abilities.
2) A climate enabler that will improve climate impact assessment and models tailored for operational mitigation concepts.
3) Analysing how operational stakeholders could bring non-CO2 mitigation technologies into their operations.
4) Investigating different air traffic management approaches to reduce the effect of persistent contrails.

Funding: €8.7 million (£7.43 million)

Funder: €4.9 million (£4.18 million) from the EU as part of the SESAR 3 Joint Undertaking

Other Key Stakeholders:

— **Industry:** Airbus, Meteo-France, Eurocontrol, DLR, Boeing Spain, Netherlands Aerospace Centre, Air France, Direction des Services de la navigation aérienne, Office National d'etudes et de Recherches Aerospatiales, Ecole Nationale de L'Aviation Civile, Forschungszentrum Jülich, SWISS International Airlines, NATS

— **Academia:** The Technical University of Catalona / BarcelonaTech, The University of Manchester

Potential research gaps

Aside from the MUAC 2021 trial, this study has not identified alternative air traffic control region wide contrail avoidance trials. There is a potential opportunity for the UK to lead on a contrail avoidance trial in the North Atlantic, which has a large amount of strongly warming and strongly cooling contrails in the region.[283] Night-time contrails have a warming effect, and so avoiding these may have a lower associated

[282] European Commission (2023). Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment. Available at: https://cordis.europa.eu/project/id/101114613

[283] Teoh, R., Engberg, Z., Schumann, U., Voigt, C., Shapiro, M., Rohs, S. and Stettler, M., 2023. Global aviation contrail climate effects from 2019 to 2021. *EGUsphere*, *2023*, pp.1-32. [preprint]

risk of avoiding cooling contrails (although contrails may survive into the next day). Researchers from NATS, Imperial College, DLR, and Cranfield have published a paper laying out design principles for a North Atlantic trial, discussing the practicalities of running a trial in the Shanwick FIR (Flight Information Region), including factors to motivate which flights to target, whether to implement tactical and/or pre-tactical deviations, which stakeholders to involve, and validation options.[284] A number of ATM strategies to reduce contrails are presented. They note that there has been a recent relaxation of separation requirements between aircraft due to satellite surveillance, and also that most of the aircraft are in cruise in the Shanwick FIR which they see as advantageous for considering contrail management.

7.3 Contrail prediction tools

The two main tools of contrail prediction are weather forecasts and satellite imagery. The former is able to step forward in time by solving the governing equations and, whilst satellite imagery only gives an update on the current state of the atmosphere, this can be used to locate contrail forming regions when contrails occur, as well as to verify contrail avoidance measures. The EU is helping to fund work in both weather forecasting and processing, and application of satellite imagery in its Better Contrails Mitigation (BeCoM) and E-CONTRAIL projects respectively.[285,286] As mentioned previously, the creation of a network of European researchers has been called for by Eurocontrol, Airbus, and Thales, to create a repository of contrail observations (e.g. satellite and ground camera imagery) and to drive the creation of AI contrail detection algorithms.[287] [288]

ARPA-E (The Advanced Research Projects Agency – Energy), a part of the US Department of Energy, has funded a number of projects which have recently begun (2023) to improve contrail prediction, an important precursor to contrail avoidance, except in the case of nowcasting, in which regions to avoid are based on previous contrail formation.[289]

An interesting theme involves the use of on-board sensors to aid in contrail prediction, with Northrup Grumman, RTX Technologies Research Centre and Boeing planning to investigate this potential in their ARPA-E projects.[290] Northrup

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[284] Molloy, J., Teoh, R., Harty, S., Koudis, G., Schumann, U., Poll, I. and Stettler, M.E., 2022. Design principles for a Contrail-Minimizing trial in the North Atlantic. *Aerospace*, *9*(7), p.375.
[285] BeCoM. (n.d.). Concept And Approach https://becom-project.eu/concept/
[286] European Commission. (2023). Artificial Neural Networks for the Prediction of Contrails and Aviation Induced Cloudiness. Available at: https://cordis.europa.eu/project/id/101114795
[287] Jarry, L, and Very, P, 2023, 'Contrail Research: The Critical Role of Observational Data & AI', Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc,3:44:12
[288] Eurocontrol. (December, 2023). Latest news on EUROCONTROL's work on sustainability. Available at: https://www.eurocontrol.int/article/latest-news-eurocontrols-work-sustainability-issue-9
[289] ARPA-E. (n.d.). Aviation Contrails. Available at: https://arpa-e.energy.gov/technologies/exploratory-topics/aviation-contrails
[290] ARPA-E. (2023). U.S Department of Energy Announces Projects Developing Technologies to Mitigate Aviation Emissions. Available at: https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-projects-developing-technologies

Grumman's radiometric temperature and humidity sensor will look to provide in situ guidance of whether contrail regions are ahead of the aircraft or not.

Both Boeing and GE (General Electric) are bringing multiple data sources together to tackle the problem in their funded ARPA-E projects.[291] This is symptomatic of the difficulty of predicting contrails, as well as perhaps a sign of scoping out of what key sources of information may end up being the key for contrail management. As with many current technology fields, machine learning/AI research is prominent.

A summary of the projects in this section is found in Table 12 on the next page.

[291] ARPA-E. (2023). U.S Department of Energy Announces Projects Developing Technologies to Mitigate Aviation Emissions. Available at: https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-projects-developing-technologies

Table 12: Summary of industry and government projects on contrail prediction tools

Project	Years	Key themes	Lead	Funders	Funding
Better Contrails Mitigation[292] (BeCoM)	2022-2026	Cloud physics, assimilation, trajectory optimisation	Delft	EU	£3.8m
Contrail Avoidance System[293]	Current	Radiometric temperature and humidity sensor for in-flight contrail avoidance	Northrop Grumman	US	£2.0m
CONtrail Forecasting through In-situ Reliable Multisourced Modeling and Sensing (CONFIRMMS)[294]	Current	On board Lidar measurements	RTX Tech Research Center	US	£2.0m
Contrail Information for Collaborative Operations (CINCO)[295]	Current	Multi-faceted approach for mitigating contrails	Boeing	US	£2.0m
Engine-informed Prediction of Aviation Induced Cirrus Trails (EPIC-Trails)[296]	Current	In-flight contrail prediction system	GE	US	£1.2m
E-CONTRAIL Project: Artificial Neural Networks for the Prediction of Contrails and Aviation Induced Cloudiness[297,298]	2023-2025	Geostationary satellite imagery & RF models, deep-learning algorithms for contrail forcing, predict climate sensitive airspace regions	UC3M	EU	£0.84m
Physics & Machine Learning Based Aviation Contrails Prediction and Observation System[299]	Current	New atmospheric data & ensemble approaches, real-time contrail prediction and avoidance system	Universities Space Research Assoc.	US	£0.79m

[292] BeCoM. (n.d.). Concept And Approach https://becom-project.eu/concept/
[293] ARPA-E. (2023). U.S Department of Energy Announces Projects Developing Technologies to Mitigate Aviation Emissions. Available at: https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-projects-developing-technologies
[294] ARPA-E. (2023). U.S Department of Energy Announces Projects Developing Technologies to Mitigate Aviation Emissions. Available at: https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-projects-developing-technologies
[295] ARPA-E. (2023). U.S Department of Energy Announces Projects Developing Technologies to Mitigate Aviation Emissions. Available at: https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-projects-developing-technologies
[296] ARPA-E. (2023). U.S Department of Energy Announces Projects Developing Technologies to Mitigate Aviation Emissions. Available at: https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-projects-developing-technologies
[297] European Commission. (2023). Artificial Neural Networks for the Prediction of Contrails and Aviation Induced Cloudiness. Available at: https://cordis.europa.eu/project/id/101114795
[298] E-CONTRAIL. (n.d.). Artificial Neural Networks for the Prediction of Contrails and Aviation Induced Cloudiness. Available at: https://www.econtrail.com/
[299] ARPA-E. (2023). U.S Department of Energy Announces Projects Developing Technologies to Mitigate Aviation Emissions. Available at: https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-projects-developing-technologies

Example project

Better Contrails Mitigation, 2022-2026

BeCoM will address the uncertainties related to the forecasting of persistent contrails and their weather-dependent individual radiative effects.

At the heart of BeCoM stands the enhancement of the physical representation of ice cloud and the treatment of ISSRs, which improves the prediction of persistent contrails, hence allowing the integration of contrail schemes in the existing policy framework to enable eco-efficient trajectories. This project is Coordinated by Delft University of Technology (Netherlands).

The five technical work packages in the project are:

1) Operational & new measurements & characterisation
2) Cloud Physics & weather models & assimilation
3) Evaluation of data and model predictions
4) Climate optimised trajectories
5) Policy-driven Flight Planning

Funding / Budget: € 4.5 million (£3.84 million)

Funder: EU

Other Key Stakeholders:

- Government: EU
- Academia: Delft, DLR, CNRS, The University of Birmingham, UVSQ
- **Industry: Thales, DWD (Deutscher Wetterdienst), ECATS, Envisa**

Potential research gaps

Humidity sensors feature significantly in the US ARPA-E funding projects. Obtaining more data, more accurately, on water vapour at flight altitudes will help in furthering contrail research. Industry in the UK is also undertaking work in this space with humidity sensors being installed with Loganair in collaboration with the Met Office and FLYHT Aerospace.[300] In the research that has been conducted so far, the use of on-board sensors to implement in-flight contrail avoidance by measuring weather variables ahead of the aircraft is not planned in the EU but has been seen in the US with e.g. Northrup Grumman. This could be an alternative mitigation approach.

[300] Loganair (2023). Loganair joins with the MET Office and FLYHT to power revolutionary sustainable aviation research. Available at: https://www.loganair.co.uk/our-story/latest-news/2023/loganair-joins-with-the-met-office-and-flyht-to-power-revolutionary-sustainable-aviation-research/

7.4 Combustor and aircraft design

Much of the combustor research in this domain is relevant to NOx since this is formed through chemical reactions in the engine, but there are a couple of exceptions. Research has been undertaken on the number of soot particles produced by an engine per kg of fuel burn. This has a large impact on the initial properties of a contrail; however, research may also be motivated by the health risks of high soot emissions near airports.

Of the projects researched, one stands out due to its very large funding in comparison to others.[301] The SWITCH (Sustainable Water-Injecting Turbofan Comprising Hybrid-electrics) project investigates a new gas turbine technology in which water is injected into the combustor,[302] and where the impact of contrails is planned to be reduced through particle removal and water recovery. A US ASCENT (The Aviation Sustainability Center)[303] project carried out by MIT has also investigated the effect of water injection into the engine and found that it reduced NOx emissions although increased persistent contrail formation – see the example project for this section below.[304]

Government funding has been invested into combustor technology in the US: the GE TAPS (Twin Annular Premixing Swirler) combustors, which have low NOx emissions, received FAA funding from the CLEEN (Continuous Lower Energy, Emissions, and Noise) Phase I and II programs to aid in their development, and the engine is now currently flying with 500 aircraft, with a further 5,000 on order.[305,306]

Only one project on aircraft design has been identified by this study; the EU GLOWOPT funded project (see details in Table 13).[307] It found that an aircraft optimised for flying at lower altitudes and Mach numbers would be significantly better for the environment, despite reduced fuel efficiency.[308] At these altitudes the impact of NOx on ozone is reduced, and contrails are less likely to form.[309] A summary of these projects is shown in Table 13 on the next page.

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301 Although this should not be interpreted as a large amount of funding dedicated to non-CO_2 rather on engine design overall which also impacts non-CO_2

302 European Commission. (2023). Sustainable Water-Injecting Turbofan Comprising Hybrid-electrics. Available at: https://cordis.europa.eu/project/id/101102006

303 The Aviation Sustainability Center is an aviation research organisation funded by several parties including the FAA. It is led by Washington State University and MIT.
Ascent. (n.d.). ASCENT – THE AVIATION SUSTAINABILITY CENTER. Available at: ascent.aero

304 Ascent. (n.d.). Project 051 Combustion Concepts for Next-Generation Aircraft Engines. Available at: https://s3.wp.wsu.edu/uploads/sites/2479/2023/05/ASCENT-Project-051-2022-Annual-Report.pdf

305 FAA. (2022). REDAC Environment and Energy Sub-Committee. Available at: https://www.faa.gov/sites/faa.gov/files/2022-03/508.20220323_1330_Ileri_Orton_Aircraft_Technology_v01.pdf

306 U.S. Department of Transportation. (2023). Advancing Next Generation Aviation Technologies. Available at: https://www.transportation.gov/advancing-next-generation-aviation-technologies#:~:text=Under%20CLEEN%20Phases%20I%20and,and%20over%205%2C000%20on%20order.

307 European Commission. (2024). Global-Warming-Optimized Aircraft Design. Available at: https://cordis.europa.eu/project/id/865300

308 Proesmans, P.J. and Vos, R., 2022. Airplane design optimization for minimal global warming impact. Journal of Aircraft, 59(5), pp.1363-1381.
Available at: https://pure.tudelft.nl/ws/portalfiles/portal/134861935/1.C036529.pdf

309 ibid

Table 13: Summary of industry & government projects on combustor and aircraft design

Project	Years	Key themes	Lead	Funders	Funding amount
Sustainable Water-Injecting Turbofan Comprising Hybrid-electrics (SWITCH)[310]	2023-2025	Turbofan, Engine water injection, hybrid electric aviation, particle removal, water recovery	MTU Aero Engines Germany	EU	£58m total, £41.5m from EU
Minimum environmental impact ultra-efficient cores for aircraft propulsion (MINIMAL)[311]	2022-2026	Combining gas turbine & piston engine, novel research, step change in emissions	Chalmers Tech University	EU/UK	£3.0m
Reduction of nvPM emissions from Aero-Engine Fuel Injectors[312]	2020-	Soot formation, reducing nvPM, fuel injectors, laser-induced incandescence measurements, numerical simulations	Georgia Institute of Technology	US	£1.2m matched by stakeholders
Predictive Simulation of nvPM emissions in aircraft combustors[313]	2020-	Chemical kinetic models for fuel decomposition and oxidation, nucleation models, soot growth models, combustor large eddy simulations	Georgia Institute of Technology	US	£1.2m matched by stakeholders
Combustor Concepts for Next-Generation Aircraft Engines[314]	2020-	Engine water injection, lean-burn radially staged combustion, NOx, engine efficiency	MIT	US	£0.77m matched by stakeholders

[310] European Commission. (2023). Sustainable Water-Injecting Turbofan Comprising Hybrid-electrics. Available at: https://cordis.europa.eu/project/id/101102006
[311] European Commission. (2022). Minimum environmental impact ultra-efficient cores for aircraft propulsion. Available at: https://cordis.europa.eu/project/id/101056863
[312] Ascent. (n.d). Project 070 Reduction of nvPM Emissions from Aero-Engine Fuel Injectors. Available at: https://s3.wp.wsu.edu/uploads/sites/2479/2023/04/ASCENT-Project-070-2022-Annual-Report.pdf
[313] Ascent, (n.d). Project 071 Predictive Simulation of nvPM Emissions in Aircraft Combustors. Available at: https://s3.wp.wsu.edu/uploads/sites/2479/2023/04/ASCENT-Project-071-2022-Annual-Report.pdf
[314] Ascent. (n.d.). Project 051 Combustion Concepts for Next-Generation Aircraft Engines. Available at: https://s3.wp.wsu.edu/uploads/sites/2479/2023/05/ASCENT-Project-051-2022-Annual-Report.pdf

Global-Warming-Optimized Aircraft Design (GLOWOPT)[315,316]	2019-2022	Optimised aircraft design and operating conditions	Hamburg Technical University	EU	£0.76m
Impact of Fuel Heating on Combustion and Emissions[317,318]	2020-	Fuel heating, NOx, engine efficiency	Purdue University	US	£0.64m matched by stakeholders
Twin Annular Premixing Swirler (TAPS_ II & III Combustors[319]	2016-2020	Combustor design, high efficiency, reduced NOx	GE	US	FAA Clean Phase II program

[315] European Commission. (2024). Global-Warming-Optimized Aircraft Design. Available at: https://cordis.europa.eu/project/id/865300
[316] GLOWOPT. (n.d.). Global-Warming-Optimized Aircraft Design. Available at: glowopt.eu
[317] Ascent. (n.d.). IMPACT ON FUEL HEATING ON COMUBSTION AND EMISSIONS. Available at: https://ascent.aero/project/impact-of-fuel-heating-on-combustion-and-emissions/
[318] Ascent. (n.d). Project 067 Impact of Fuel Heating on Combustion Emissions. Available at: https://s3.wp.wsu.edu/uploads/sites/2479/2023/04/ASCENT-Project-067-2022-Annual-Report.pdf
[319] FAA. (2022). REDAC Environment and Energy Sub-Committee. Available at: https://www.faa.gov/sites/faa.gov/files/2022-03/508.20220323_1330_Ileri_Orton_Aircraft_Technology_v01.pdf

Example project

Combustion Concepts for Next-Generation Aircraft Engines, 2020-current[320]

This project, part of the ASCENT program, was run by MIT. Engine cycles increase in efficiency with higher peak temperatures and pressures, but this tends to result in higher NOx emissions. This project investigated two combustion concepts which may alleviate the trade-off: water injection, and lean-burn radially staged combustion.

The following details from the project are taken from the 2022 annual report. The 2023 report, if it is to be produced, has not been released. The project found that water injection reduced NOx emissions, and that the engine efficiency rises too if the water is injected before the low-pressure compressor, or high-pressure compressor. Since carrying water on the aircraft had a weight cost, it was found that the trade-off between fuel consumption (which increases with weight) and NOx emissions was better for short-range flights. Unfortunately, the project also found that the additional water injection led to a rise in persistent contrail formation.

For the project's second task, the aim was to investigate how the NOx production would vary when the ratio of fuel injection between two flames in learn-burn radially staged combustors was varied. An example of that combustor are the TAPS and TAPS II combustors. Outputs of the project included improved understanding of how the optimal fuel ratio changed with phases of flight (and levels of thrust). Results from both stages of this project were released.

Funding: $900,000 (£769,341) FAA funding, $900,000 matched funds (MIT and NuFuels LLC)

Other Key Stakeholders:

- Government: ASCENT Program (US)
- Academia: MIT

Potential research gaps

For an up-to-date assessment of this issue the ATI may be able to provide further insight. This work has already begun in the ATI through the Destination Zero Strategy[321] and their Non-CO_2 Technology Roadmap[322].

[320] Ascent. (n.d.). Project 051 Combustion Concepts for Next-Generation Aircraft Engines. Available at: https://s3.wp.wsu.edu/uploads/sites/2479/2023/05/ASCENT-Project-051-2022-Annual-Report.pdf

[321] ATI Destination Zero Strategy https://www.ati.org.uk/wp-content/uploads/2022/04/ATI-Tech-Strategy-2022-Destination-Zero.pdf

[322] ATI Non-CO2 Technology Roadmap https://www.ati.org.uk/wp-content/uploads/2024/03/ATI-Non-CO2-Technologies-Roadmap-Report-FINAL-March-2024.pdf

7.5 Sustainable Aviation Fuels (SAF)

SAF has been suggested as an attractive mitigation option to reduce both CO_2 and contrail cirrus.[323] Several in-flight experiments have been run, most recently in 2023 with both Airbus and Boeing, involving a SAF burning aircraft and a chaser plane taking measurements. This follows promising results from a 2018 flight trial (part of the ECLIF II program) which found reduced ice crystal concentrations and increased crystal sizes from young contrails, which some modelling studies have suggested leads to reduced radiative forcing.[324,325] Summaries of the projects is shown in Table 14 on the next page.

Further research in this field is being conducted through an ongoing US ASCENT program which is looking to run experimental tests and bring together modelling studies to further understanding of contrail formation, including formation when using SAF, as shown in the project example.

[323] Teoh, R., Schumann, U., Voigt, C., Schripp, T., Shapiro, M., Engberg, Z., Molloy, J., Koudis, G. and Stettler, M.E., 2022. Targeted use of sustainable aviation fuel to maximize climate benefits. *Environmental Science & Technology*, *56*(23), pp.17246-17255.

[324] Voigt, C., Kleine, J., Sauer, D., Moore, R.H., Bräuer, T., Le Clercq, P., Kaufmann, S., Scheibe, M., Jurkat-Witschas, T., Aigner, M. and Bauder, U., 2021. Cleaner burning aviation fuels can reduce contrail cloudiness. *Communications Earth & Environment*, *2*(1), p.114.

[325] Burkhardt, U., Bock, L. and Bier, A., 2018. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. *npj Climate and Atmospheric Science*, *1*(1), p.37.

Table 14: Summary of industry & government projects on the impact of sustainable aviation fuel on contrails

Project	Years	Key themes	Lead	Funders
RefuelEU aviation initiative[326]	2023	Minimum % of SAF obligation	EU	
Assessment of contrail formation via combustion of sustainable aviation fuel[327]	Current	Researching physics of contrail formation, laboratory experiments, SAF	University of Illinois	US
Boeing ecoDemonstrator[328]	2023	SAF, in flight contrail research experiments	Boeing	
Volcan[329][330]	2023	SAF, in flight contrail research experiments	Airbus	Co-funded by CORAC[331]
Emission and Climate Impact of Alternative Fuels (ECLIF)[332]	2015, 2018	SAF, In flight contrail research experiments	DLR & NASA	
Alternative Fuel Effects on Contrails and Cruise Emissions (ACCESS) I, II[333]	2013, 2014	Biofuels, In flight contrail research, engine emissions	NASA	

[326] European Council. (2023). RefuelEU aviation initiative: Council adopts new law to decarbonise the aviation sector. Available at: https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/#:~:text=The%20obligation%20for%20aviation%20fuel%20suppliers%20to%20ensure,fuels%2C%20with%20both%20shares%20increasing%20progressively%20until%202050.

[327] Ascent. (2023). ASSESSMENT OF CONTRAIL FORMATION VIA COMBUSTION OF SUSTAINABLE AVIATION FUEL. Available at: https://ascent.aero/project/assessment-of-contrail-formation-via-combustion-of-sustainable-aviation-fuel/

[328] Polek.G. (2023) Latest Boeing EcoDemonstrator Studies Tackle SAF's Contrail Effects, https://www.ainonline.com/aviation-news/air-transport/2023-11-05/latest-boeing-ecodemonstrator-studies-tackle-safs-contrail

[329] Airbus. (2023). Airbus' most popular aircraft takes to the skies with 100% sustainable aviation fuel. Available at: https://www.airbus.com/en/newsroom/stories/2023-03-airbus-most-popular-aircraft-takes-to-the-skies-with-100-sustainable

[330] Volcan stands for Vol avec Carburants Alternatifs Nouveaux – Flight with new alternative fuels.

[331] The French Council for Civil Aeronautical Research, https://www.airbus.com/en/newsroom/stories/2023-03-airbus-most-popular-aircraft-takes-to-the-skies-with-100-sustainable

[332] Gipson. (2021). NASA-DLR Study Finds Sustainable Aviation Fuel Can Reduce Contrails. Available at: https://www.nasa.gov/news-release/nasa-dlr-study-finds-sustainable-aviation-fuel-can-reduce-contrails/

[333] Banke. (2013). NASA Researchers Sniff Out Alternate Fuel Future. Available at: https://www.nasa.gov/aeronautics/nasa-researchers-sniff-out-alternate-fuel-future/

Example project

Assessment of contrail formation via combustion of sustainable aviation fuel, current[334]

The goal of the project is to conduct experimental and modelling work to:

(1) understand the physics of contrail formation using advanced laser and optical diagnostics;

(2) investigate contrail formation for fuels with varying composition, including Sustainable Aviation Fuels (SAF); and,

(3) integrate test data with environmental modelling teams and other flight-based tests. Contrails are composed primarily of water (in the form of ice crystals), and generally evaporate quickly.

The main benefit of this project is to conduct highly controlled laboratory experiments coupled with high fidelity laser and optical diagnostics to create a scientific foundation for understanding contrail formation.

Other Key Stakeholders:

- Government: ASCENT program (US), NASA
- Academia: University of Illinois
- Industry: Sandia National Laboratories

Potential research gaps

Banke, 2013 recommended that further experimental observations be made on the impact of SAF on persistent contrails as there is no definitive analysis.[335] As the nvPM emissions reduce from an engine, other aerosols may be activated to form ice crystals. Some work has been undertaken on investigating the role of engine lubrication oils as a potential source of nucleation by researchers at Leeds University and Imperial College, and they recommended additional work in this area.[336] When results from the 2023 flight trials are published, additional next steps for the industry may be made clear. The ASCENT contrail formation project above indicates that the initial contrail formation stages are not yet fully understood and warrant further research.

Teoh *et al.,* 2022, suggested that targeting specific flights (e.g., nighttime flights, or those indicated to be particularly warming when running a contrail prediction model)

[334] Ascent. (2023). ASSESSMENT OF CONTRAIL FORMATION VIA COMBUSTION OF SUSTAINABLE AVIATION FUEL. Available at: https://ascent.aero/project/assessment-of-contrail-formation-via-combustion-of-sustainable-aviation-fuel/

[335] Stettler. M, 2023, Sustainable Skies Conference: Contrails in Focus, 8th November 2023

[336] Ponsonby, J., King, L., Murray, B.J. and Stettler, M.E., 2024. Jet aircraft lubrication oil droplets as contrail ice-forming particles. *Atmospheric Chemistry and Physics*, *24*(3), pp.2045-2058.

to use SAF could reduce contrail radiative forcing significantly.[337] Research as to whether this could be practically implemented from an airport and logistics perspective could be valuable, and if so, what technology enablers would require further research.

7.6 Non-CO_2 impacts

Uncertainties around non-CO_2 impacts from aviation are much larger than with CO_2, and so it is valuable for research to continue in this field. There is crossover here with other categories – notably Contrail Prediction Tools, for which BeCoM and E-CONTRAIL are current projects which are aiming to improve understanding of contrails. Lee *et al.,* 2023,[338] noted the uncertainty associated with radiative forcing estimates from contrails, and the E-CONTRAIL project plans to bring together satellite imagery and radiative transfer models to quantify radiative forcing in ice clouds, and then predict contrail RF. This work may help to reduce the uncertainty associated with RF calculations.

In addition, the ASCENT project on the 'Assessment of contrail formation via combustion of sustainable aviation fuel' may provide valuable insight into the early stages of contrails. The EU funded ACACIA project ran for 4 years (Jan 2020 – Feb 2024) and contributed research on contrail radiative forcing as well as broader research on cirrus.

A summary of these projects is shown in Table 15.

[337] Teoh, R., Schumann, U., Voigt, C., Schripp, T., Shapiro, M., Engberg, Z., Molloy, J., Koudis, G. and Stettler, M.E., 2022. Targeted use of sustainable aviation fuel to maximize climate benefits. *Environmental Science & Technology*, *56*(23), pp.17246-17255.

[338] Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P. and Skowron, A., 2023. Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), pp.1693-1740.

Table 15: Summary of industry & government projects on non-CO2 impacts. There is significant crossover with the other sections including BeCoM and E-CONTRAIL research

Project	Years	Key themes	Lead	Funders	Funding amount
The Impact of non-CO2 Aviation Climate Effects[339]	2020	EU ETS, review of non-CO2 impacts	EASA		
Constrained aerosol forcing for improved climate projections (FORCeS)[340]	2019-2024	Not aviation specific, impact of aerosols on climate	Stockholm University	EU	£6.8m
Advancing the Science for Aviation and ClimAte (ACACIA)[341]	2020-2024	Targeting uncertainty, NOx, contrails	DLR	EU	£2.6m
Contrail and Cirrus Experiment (CONCERT)[342]	2008, 2011	In flight contrail properties measurements	DLR		
The Contrail Observation Program (COOP)[343]	2022	Contrail observation program: in-flight and ground based	Air France		

[339] EASA. (2020). Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4). Available at: https://www.easa.europa.eu/sites/default/files/dfu/201119_report_com_ep_council_updated_analysis_non_co2_climate_impacts_aviation.pdf
[340] European Commission. (2023). Constrained aerosol forcing for improved climate projections. Available at: https://cordis.europa.eu/project/id/821205
[341] European Commission. (2023). Advancing the Science for Aviation and ClimAte. Available at: https://cordis.europa.eu/project/id/875036
[342] DLR. (n.d). CONCERT. Available at: https://www.pa.op.dlr.de/CONCERT/
[343] Curat, V & Pechaud, L, 2023, 'Prediction of contrail formation & Observation process', Sustainable Skies Conference: Contrails in Focus, https://www.youtube.com/watch?v=0fPThUSHnxc&t=7841s, 4:42:30

Example project

CONCERT (Contrail and Cirrus Experiment) Campaign, 2008, 2011

In flight measurements were taken behind Airbus test aircraft and Lufthansa passenger aircraft. The planned focus of the campaign was the data collection and analysis to determine microphysical, chemical, and radiative properties of contrails and cirrus clouds (see references).

A number of papers were published presenting and interpreting the processed data. For example, Voigt *et al.,* 2011, estimated the optical depth of contrails measured in the 2008 flight tests. Kubbeler *et al.,* 2011, published results showing that contrails can persist in subsaturated regions.

Funding: $900,000 (£769,341) FAA funding, $900,000 matched funds (MIT and NuFuels LLC)

Other Key Stakeholders:

- Academia: DLR
- Industry: Airbus

Potential research gaps

Attaining an improved parameterisation of changes in ice crystal geometries during a contrail lifetime has not been seen in the projects which have been identified by this study. More research could be undertaken in developing a higher fidelity version of CoCiP (albeit this may be met in part through the E-Contrail project). MIT worked on this problem, developing such a model,[344] but found that it was too computationally expensive to be run at very short notice to enable near-real time decision making.[345] Subsequent model changes were planned. Further work in this field could be valuable in improving radiative forcing estimates from individual flights. Additional in-flight experiments would be useful to both validate and constrain models.

7.7 Conclusion

Both EU and US Government bodies are taking non-CO_2 seriously with many projects underway working to improve mitigation techniques and improving theoretical understanding. Many of the new projects are quite broad in scope with full details not yet published providing a deeper understanding of activities and outcomes, making it difficult to identify clear gaps. The current research findings have been explored in the literature review, however over and above this, academic projects (other than those as part of a consortium detailed here) are not fully included as there is limited sight of it prior to publication. The projects show that industry has not converged on one given mitigation strategy yet, with research being

[344] Fritz, T.M., Eastham, S.D., Speth, R.L. and Barrett, S.R., 2020. The role of plume-scale processes in long-term impacts of aircraft emissions. *Atmospheric Chemistry and Physics*, *20*(9), pp.5697-5727.
[345] https://s3.wp.wsu.edu/uploads/sites/2479/2023/06/ASCENT-Project-078-2022-Annual-Report.pdf

undertaken in advanced combustion technologies which would mitigate non-CO_2, the role of SAF in reducing contrail cirrus, contrail avoidance through nowcasting with satellite imagery, and contrail avoidance using weather forecasts. A few potential areas for UK Government to consider have been noted, including considering following on from the MUAC and NATS ATC trials, perhaps over the North Atlantic.

8 Conclusion and next steps

The detailed investigation into the non-CO_2 impacts of aviation, as delineated in this report, underscores the complexity and significance of these impacts on climate change. The non-CO_2 impacts, including contrails and cirrus clouds, nitrogen oxides, water vapour, and aerosol-radiation and aerosol-cloud interactions, collectively represent a critical component of aviation's overall climate footprint. While CO_2 emissions have historically dominated climate policies and mitigation strategies, this report highlights the urgent need to broaden the scope to include non-CO_2 impacts comprehensively.

The literature review reveals a burgeoning academic and industry focus on these impacts, with notable emphasis on contrails and NOx emissions. However, it also uncovers substantial gaps in understanding and quantifying these effects accurately. These gaps hinder the development of effective mitigation strategies and policies. The evaluation of existing methodologies and metrics underscores the need for improved measurement and monitoring tools, underscoring the challenges in drawing definitive conclusions about the magnitude and implications of these impacts.

This report identifies several potential mitigation strategies, including the development of alternative fuels, aircraft and engine design innovations, optimised flight planning, and in-flight avoidance techniques. However, the implementation of these strategies is contingent upon overcoming significant technological, economic, and regulatory hurdles. Moreover, the interplay between CO_2 and non-CO_2 impacts necessitates a holistic approach to mitigation, acknowledging potential trade-offs and co-benefits.

8.1 Key conclusions and findings from the report

8.1.1 Literature review of identified existing research on aviation's non-CO2 impacts

This chapter underlines the importance of recognising the complexity and variability of non-CO_2 impacts from aviation, addressing the significant uncertainties in their climate impact assessment, and enhancing measurement and modelling methods to inform more effective environmental policies and mitigation strategies.

Key findings include:

1) **Complexity and variability in non-CO_2 impacts:** The impacts of aviation's non-CO_2 emissions, like contrails, NOx, and aerosols, are more complex and variable than CO_2. These impacts differ in their formation, behaviour, and interactions within the atmosphere. The report emphasises the understanding these variable effects is critical but challenging, adding significant complexity to climate modelling and predictions.

2) **Significant uncertainties in climate impact assessment:** There is considerable uncertainty in understanding the overall climate impact of these non-CO_2 emissions. This uncertainty arises from their transient nature, the variability of their impacts based on several factors (like atmospheric conditions, time of day, and geographical location), and their intricate interactions within the atmosphere. These factors make it difficult to accurately predict and model their total impact on global warming.

3) **Challenges in measurement and modelling:** Accurately measuring and quantifying the concentration of non-CO_2 emissions such as NOx, aerosols, and contrails present significant challenges. These challenges are primarily due to the limitations of current measurement tools, technologies and methodologies, contributing to the uncertainties in understanding these impacts. There's a need for more advanced observational techniques and modelling tools to capture these complex emissions accurately. Developing more **robust tools for observations is therefore needed,** including independent validation tools and improved global satellite validation to provide more accurate weather data.

4) **Policy and research implications:** There are gaps in our understanding and prediction of aviation's overall climate impact due to these non-CO_2 emissions. Current climate models may not fully account for the transient and localised effects of non-CO_2 impacts. This has significant implications for climate modelling and the development of effective environmental policies and mitigation strategies. The conclusion underscores the need for improved methodologies, comprehensive climate modelling, and further research to inform policy decisions effectively.

8.1.2 Mitigation strategies and challenges

Mitigating aviation's non-CO_2 climate impacts requires a multifaceted approach involving research, innovation, operational adjustments, stakeholder collaboration, and public engagement. By addressing these challenges, the aviation industry can contribute to a more sustainable future.

Key findings include:

1. Contrail formation mitigations: Contrails are a significant contributor to aviation's non-CO_2 climate impact, potentially exceeding CO_2 emissions in certain cases. Contrail formation is influenced by atmospheric conditions, particularly temperature, humidity, and pressure. Various mitigation strategies have been explored to reduce contrail formation, including:

- **Alternative fuels:** Sustainable Aviation Fuel (SAF), hydrogen, and ammonia show potential in reducing contrail formation and emissions.
- **Aircraft and engine design:** Improvements in aircraft and engine design can reduce NOx emissions and contrail formation.

- **Optimised flight planning:** Adjusting flight paths and altitudes can avoid areas prone to contrail formation.
- **In-flight avoidance:** Real-time adjustments to flight paths can avoid areas with existing contrails.
- **Lower flight altitude:** Flying at lower altitudes can reduce contrail formation, but may increase fuel consumption.
- **Daytime flight only:** Maximising flights **during** daytime hours can reduce the warming effect of contrails.
- **Formation flights:** Flying in formation can reduce the net contrail effect.

2. NOx emissions mitigations: NOx emissions from aircraft contribute to ozone formation and have a warming effect on the atmosphere. Mitigation strategies for NOx emissions include:

- **Alternative fuels:** Hydrogen has the potential to reduce NOx emissions.
- **Aircraft and engine design:** Advancements in engine technology can reduce NOx emissions.
- **Optimised flight planning:** Adjusting flight paths and altitudes can reduce NOx emissions.

3. Other non-CO_2 impacts and mitigations: Aviation also contributes to other non-CO_2 climate impacts, such as emissions of non-volatile particles (nvPM) and water vapor. Mitigation strategies for these impacts are still under development.

4. Challenges and uncertainties: Despite promising advancements in mitigating aviation's non-CO_2 climate impacts, several challenges and uncertainties remain. The limited availability of SAF hinders hits widespread adoption. Technological hurdles impede the development of cleaner engine technologies that effectively reduce NOx emissions. Accurately predicting contrail formation and its climate impact requires sophisticated atmospheric modelling, which presents a significant challenge. Implementing mitigation strategies often faces operational complexities, requiring adjustments to air traffic management and flight planning. Additionally, scientific uncertainties persist in quantifying the precise climate impact of non-CO_2 emissions, necessitating further research and refined climate metrics and tools are required to collect the required data. Addressing these challenges and uncertainties is crucial for effectively mitigating aviation's non-CO_2 climate impact and achieving a more sustainable future for the industry.

5. Key recommendations and next steps:

- **Intensifying research efforts:** To effectively address aviation's non-CO_2 climate impact intensifying research efforts to understand the full climatic impact of non-CO_2 emissions is essential. This involves conducting targeted studies, collecting, and analysing data, and developing models to better quantify the effects of these emissions on climate.

- **Developing and refining climate metrics:** This can accurately quantify the impact of both CO_2 and non-CO_2 emissions is necessary. This includes developing metrics that can capture the radiative forcing and other climate effects of non-CO_2, as well as integrating these metrics with existing CO_2 metrics.
- **Implementing mitigation strategies:** Implementing mitigation strategies with a focus on environmental optimisation and collaboration is crucial. This involves prioritising strategies that maximise climate benefits while minimising trade-offs and fostering collaboration among stakeholders across the aviation industry and research communities.
- **Engaging the public in understanding and addressing aviation's climate impact**: This involves raising awareness about the issue, promoting sustainable travel choices, and encouraging public support for policies and initiatives that promote a more sustainable aviation sector. By taking these steps, the aviation industry can contribute to a more sustainable future and mitigate its impact on the climate.

8.1.3 Evaluation of the existing methodologies and metrics to measure the non-CO2 impacts of aviation

This chapter concludes that there is a critical need for improved measurement and monitoring tools to better understand and address the non-CO_2 impacts of aviation. It calls for a multifaceted, holistic approach to mitigation, integrating technological, operational, and policy strategies, and underscores the importance of developing comprehensive metrics to guide effective climate policy and decision-making in the aviation sector.

Non-CO_2 impacts from aviation, particularly contrail formation and NOx emissions, are significant and can rival or even exceed the impact of CO_2 in certain cases. However, their short residence time makes their impact concentrated in the near-term, posing challenges for comparison with CO_2's long-term effects. Existing climate metrics, like GWP100, have limitations and can lead to variations in temperature outcomes depending on the chosen metric and timescale. Therefore, a single metric is insufficient to capture the full picture. Instead, a suite of metrics, potentially including but not limited to GWP100, GWP20, GTP100, GTP20, and GWP*, is needed to address the complex nature of non-CO_2 impacts, considering different timescales and policy needs. This will provide a more comprehensive understanding of the climate impact of aviation and inform effective mitigation strategies.

Key findings include:

1. Necessity for improved measurement and monitoring tools: The current tools for measuring and monitoring aviation's non-CO_2 impacts have limitations, particularly in terms of accuracy and comprehensiveness. Due to these limitations, it's challenging to accurately assess the magnitude and implications of non-CO_2 impacts, which is crucial for effective policy and mitigation strategy formulation.

2. Requirement for a multifaceted mitigation strategy: There is a need for a multifaceted strategy to mitigate the non-CO_2 impacts of aviation. This includes a combination of technological innovations, operational adjustments, and policy changes.

3. Holistic approach to climate impact mitigation: The report highlights the interconnected nature of CO_2 and non-CO_2 impacts. Addressing these impacts effectively requires a holistic approach that considers both types of emissions and their potential trade-offs. There is a need for a holistic approach for developing comprehensive policies and mitigation strategies that address the overall climate impact of the aviation sector.

4. Metric choice depends on the application: each metric captures a different aspect of climate change on a specific time frame. Therefore, metric choice depends on what question is being asked (e.g. what is the contribution of this sector towards the Paris Agreement's temperature goal in 2050, or what is the overall contribution of this aircraft to climate change over its lifetime?). It is therefore not possible to identify a single metric that would fulfil all uses within the aviation sector.

5. Development of comprehensive climate metrics: There is a need for the development of a suite of metrics to quantify the impact of non-CO_2 emissions. This suite would allow stakeholders to prioritise metrics based on specific policy needs and goals. There is a need to refine existing climate metrics to more accurately capture the complex and variable impacts of non-CO_2 emissions, ensuring that mitigation strategies are based on reliable and comprehensive data. At minimum, long- and short-lived forcings should be targeted separately.

6. **Separate targets and reporting for short- and long-lived forcings:** this would be a minimum requirement in order that temperature implications can be analysed. Combining short- and long-lived forcings means that temperature outcomes are ambiguous.

8.1.4 Gap assessment and policy considerations

A comprehensive, integrated policy framework, combined with continuous research, technological innovation, and active stakeholder engagement, is essential for effectively addressing the non-CO_2 impacts of aviation.

Key findings include:

1. Absence of an integrated policy framework: There is a lack of a comprehensive policy framework that simultaneously addresses both CO_2 and non-CO_2 impacts of aviation. The current focus is predominantly on CO_2 emissions, which results in the oversight of significant non-CO_2 impacts. This absence underscores the need for policy development that integrates both types of emissions, considering their collective impact on climate change.

2. Need for comprehensive impact assessment: The report emphasises the urgent requirement for a comprehensive approach to assess the climate impacts of aviation, encompassing both CO_2 and non-CO_2 emissions.

3. Importance of stakeholder engagement and regular monitoring: Ongoing engagement with stakeholders across the aviation sector is deemed crucial. This involves ensuring that research and mitigation strategies align with industry capabilities and constraints. Additionally, establishing a regular mechanism for monitoring and reviewing the progress in understanding and mitigating non-CO_2 impacts is essential. This ensures that emerging scientific knowledge and best practices are continuously integrated into aviation climate policies and regulations.

4. Recommendations for future research and focus areas:

- **Interdisciplinary collaboration:** utilise and enhance Government's non-CO_2 Research Programme to further encourage enhanced collaboration between academia, industry, and government to address the complex challenges posed by aviation's non-CO_2 impacts.
- **Technological innovations and policy integration**: the need for investment in research and development of new technologies and fuels is highlighted, alongside the importance of incorporating non-CO_2 impacts into aviation climate policies and regulations. This should build on pre-existing programme such as those made by the Aerospace Technology Institute.
- **Comprehensive models and impact assessment**: prioritising the development of models that accurately assess various emissions, considering potential trade-offs and interdependencies (for example in navigational contrail avoidance with fuel burn), is recommended. This includes continuing to improve and implement accurate parameterisations of atmospheric processes (such as vertical velocities around cirrus clouds for soot-cloud interactions, or contrail ice cloud physics processes) for use in large climate models which can estimate the radiative impact of the different non-CO_2 terms. These may be guided by further observations, which can help to constrain models.
- **Specific focus areas include**:
    - **The climate impact of contrails**, including continued research on contrail physics and radiative processes, the RF/ERF ratio, the surface temperature impact of contrails, and the development of more contrail models.
    - **Observations and subsequent processing**: models need observations to aid their development and to validate them. More contrail observations may aid in contrail model development and reducing current uncertainties. Weather models used for pre-tactical contrail avoidance may be improved by more and higher resolution water vapour measurements in the atmosphere which can be shared in real time to feed into weather models to better forecast accuracy.

Contrail detection algorithms from satellite imagery have been developed in the US and there are similar European efforts underway.

- **Contrail mitigation strategies uncertainties**: further research and modelling of the impact of low soot emissions on contrail forcing will also give more clarity on the role that SAF, the hydrotreating of fuels, or low soot combustors may have in contrail mitigation. Additionally, investigating and modelling the air traffic management requirements resulting from many aircraft implementing contrail management in a given airspace would be beneficial.
- **The climate impact of NOx**: further modelling of the RF and ERF resulting from NOx emissions will help improve confidence in its estimated impact, as well as giving improved understanding about the relative size of the ozone and methane impacts.
- **The climate impact of aerosol-cloud interactions**: further research and modelling is needed to converge towards a radiative forcing estimate for aerosol-cloud (sulfur-cloud and soot-cloud) interactions. For soot-cloud interactions, this may involve improving models of the ice nucleating ability of soot particles, as well as implementing accurate models of the vertical velocity around cirrus clouds.

The report underscores the urgency of a multifaceted approach to understanding and mitigating aviation's non-CO_2 impacts. By addressing the identified research priorities and methodological developments, stakeholders can make significant strides towards a more sustainable and environmentally responsible aviation sector.

8.1.5 Summary of recommendations

The summary of all of the identified recommendations and future considerations are:

- **<u>Enhanced interdisciplinary collaboration:</u> Foster closer collaboration between academia, industry, and government to address the multifaceted challenges posed by aviation's non-CO_2 impacts** (for example through the existing wider Non-CO_2 Research Programme). This could build on the work of the Non-CO_2 Task and Finish Group and take the form of regular forums and workshops that bring together experts from academia, industry, and government to share knowledge, collaborate on research projects, and develop joint solutions.

- **<u>Methods and metrics</u>**: A suite of metrics should be developed, in collaboration with industry stakeholders to define the most appropriate metrics to be used both in terms of the policy they are being used to measure and in ability to be adopted and used by the industry.
- **<u>Policy integration:</u> There is currently no integrated policy framework that accounts for both CO_2 and non-CO_2 impacts.** Current policies tend to prioritise CO_2 emissions, thereby neglecting the substantial contribution of non-CO_2 impacts to global climate change. Incorporate non-CO_2 impacts into aviation climate policies, ensuring that these impacts are accounted for in regulatory frameworks and mitigation strategies. This could include conducting

comprehensive assessments of existing aviation climate policies and regulations to identify gaps and opportunities for incorporating non-CO_2 impacts. It will also be key to collaborate with international organisations and governments to harmonise aviation climate policies and ensure a consistent approach to addressing non-CO_2 impacts.

- <u>Technological innovation:</u> **Encourage investment in research and development of new technologies and fuels that can reduce both CO_2 and non-CO_2** impacts from aviation through technology demonstration projects and pilot programmes. This should consider the ATI's recently published non-CO_2 roadmap[346] which will be used to inform the wider non-CO_2 research programme.
- <u>Comprehensive impact assessment:</u> **Prioritise the development of comprehensive models that can accurately assess the climate impact of various emissions (including both CO_2 and non-CO_2), considering the interdependencies and potential trade-offs**. These could be used to inform policy decisions and mitigation strategies, ensuring that they are based on a comprehensive understanding of the climate impacts of aviation.
- <u>Stakeholder engagement:</u> **Continue to engage with stakeholders across the aviation sector to ensure that the research and mitigation strategies align with industry capabilities and constraints**.
- <u>Regular monitoring and review:</u> **Establish a mechanism for regular monitoring and review of the progress in understanding and mitigating aviation's non-CO_2 impacts**, adapting strategies as new insights emerge. This will ensure that the latest scientific knowledge and best practices are incorporated into aviation climate policies and regulations.
- **<u>Research focus areas</u>:** There is already significant academic and industry research focus on non-CO_2 impacts, with notable emphasis on contrails and NOx emissions. However, there are also **substantial gaps in understanding and quantifying these effects accurately.** These gaps hinder the development of effective mitigation strategies and policies. Recommended research areas include:
  - **Estimating relative significance:** Increasing confidence in how different forcings from different non-CO_2 impacts compare would aid policy development.
  - **High accuracy models:** Developing accurate parameterisations of complicated processes that can be used in models is essential.

[346]Advanced Technology Institute. (2024). Non-CO2 Technologies Roadmap. Available at: https://www.ati.org.uk/wp-content/uploads/2024/03/Non-CO2-Technologies-roadmap-FINAL-March-2024.pdf

- — **Climate impact from contrails:** Improved representation of contrail properties, processes, and radiative transfer calculations are needed to reduce uncertainties.
- — **NOx:** Further work is required to understand the overall impact of nitrogen oxides (NOx) on the climate as they have both cooling and warming effects.
- — **Aerosol-cloud interactions**: Further work is required to consider the extent and magnitude of these impacts, which are currently not fully understood.
- — **Trade-off with CO_2**: Improved understanding of the overall climate impact for each non-CO_2 impact, and comparison between each so that the overall climate impact of any developed mitigations can be considered (e.g. where trade-offs are needed between different impacts, such as between CO_2 and NOx emissions).
- — **Atmospheric water vapour:** improved modelling and measurements of water vapour at aircraft altitudes, especially for ice super-saturated regions and contrail-cirrus formation.
- — **Alternative fuels (SAF and hydrogen):** Additional research needs to be undertaken on the impact of SAF and hydrogen on contrail cirrus and mitigation strategies for reducing soot emissions and water vapour.

- **Tool development:** Developing more robust tools for observations is necessary – as there remain ongoing challenges in observing and measuring aspects of non-CO_2 impacts. The importance of independent validation tools and improved global satellite validation to provide more accurate weather data has also been highlighted by this study.

Appendix A: Methodology

This section details the approach to the literature review including identification and review of the academic and non-academic literature and engaging with industry stakeholders.

Literature review

Define search terms and inclusion criteria:

The academic literature search focused on three principal topics: (i) contrails, (ii) NOx, and (iii) metrics, with the subtopics outlined as follows:

- Climate impact of contrails and NOx
- Uncertainty of contrail cirrus climate impact
- Advances in understanding contrail formation, persistence, and climate change impact
- NOx formation and its climate impact, e.g., ozone formation and trade-offs with other environmental factors
- Solutions to reduce uncertainty in quantifying contrail's climate impact
- Technological/operational solutions to reduce NOx emission (e.g., aircraft engine, combustion technology, fuel, air traffic management, flight planning, etc.)
- Mitigation strategies to reduce contrail-cirrus formation, longevity and impact on climate (e.g., alternative fuels, fuel efficiency, re-route, Air Traffic Management (ATM), etc.)
- Mitigation strategies to reduce NOx impact on climate change
- Metrics to measure/monitor/quantify the impact of contrail/NOx/non-CO_2 emissions on climate change
- Metric selection: exploring the impact of different metrics with different time horizons on decision-making.

Alongside the contrails, NOx and metrics, the search also included “non-CO_2 emissions” as a separate topic, aiming to encompass literature on the climate impact and relevant mitigation strategies of aviation’s non-CO_2 emissions apart from the NOx and contrails. The search terms and screening approaches were agreed between the project team and the DfT.

Search strategy - academic literature

The “Scopus” search engine was employed to explore the relevant academic literature from the last decade, between 2013 and 2023. Several steps were taken to search and acquire the critical academic literature, including: 1) initial literature search; 2) screening based on abstracts; and 3) establishing the project-specific literature database.

Step 1: Initial literature searches and list

The search terms (keywords) generated from the defined search topics, were applied to examine the abstracts, titles, and keywords of the documents within the Scopus database. The search was restricted to English-language content exclusively.

The number of initial search outcomes for each topic is shown in the table below. After eliminating the duplicates in the outcomes from different topic searches, the number of academic documents (including journal papers, conference proceedings and book chapters) initially collected was 716, distributed among topics: 277 for contrails, 50 for non-CO_2, 104 for metrics, and 285 for NOx. Please note that the search results under different topics may not be exclusively restricted to the specified topic. For instance, the 277 documents on the "contrails" topic may also encompass contents related to "metrics" and "NOx" topics.

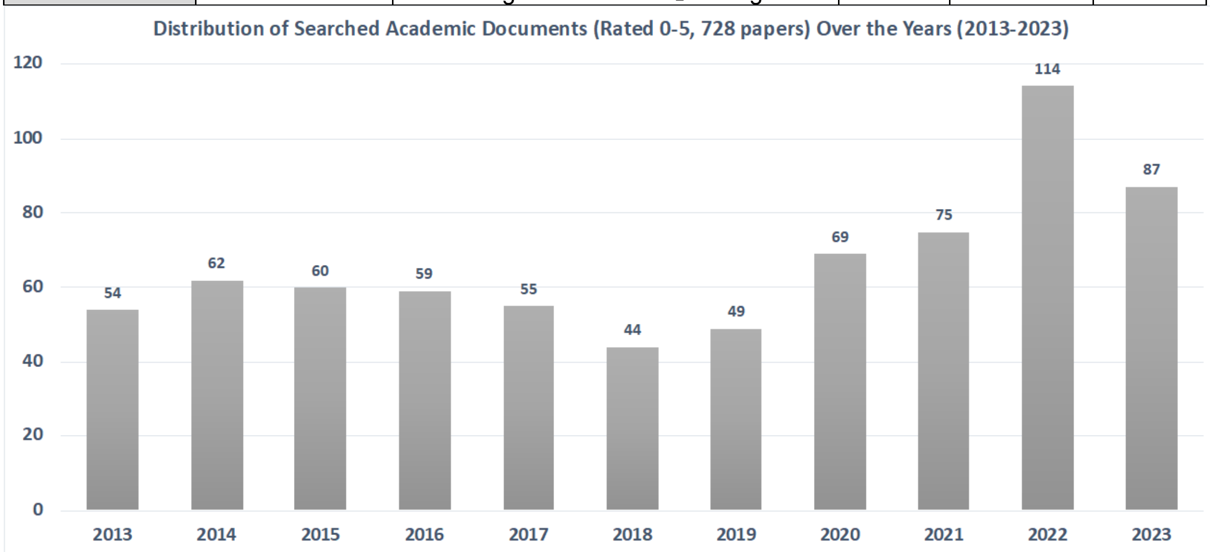
The critical information of all 716 documents was exported into one spreadsheet, including titles, authors, published years, abstracts, keywords, and date of issue. In addition, this initial search list included 12 other academic papers from the reference list of SATAVIA's contrail research. i.e., a total of 728 academic documents in the initial list. The distribution of searched academic papers over the years (2013 – 2023) is shown in the charts below.

Search Terms for Academic and Non-Academic Literature

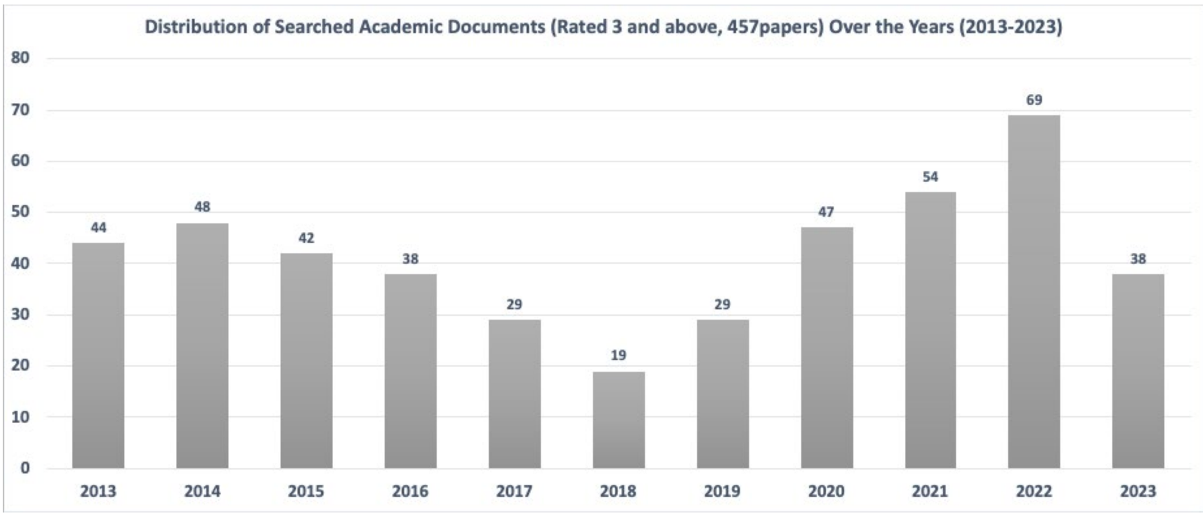
<table>
<tr><th colspan="3">Search terms （Keywords）</th><th rowspan="2">Results from Scopus</th><th rowspan="2">Results after removing duplicates</th><th rowspan="2">Major Topic</th></tr>
<tr><th>Search terms 1</th><th>Search terms 2</th><th>Search terms 3</th></tr>
<tr><td rowspan="3">aviation OR aircraft OR "air traffic" OR "air transportation"</td><td rowspan="3">AND
Contrail OR "contrail cirrus" OR cirrus OR "contrail overlapping" OR "contrail-contrail overlapping" OR "linear contrails" OR "persistent contrail" OR "short-lived contrail" OR "long-lived contrail" OR "cirrus cloud" OR "aviation-induced contrail cirrus"</td><td>AND
"climate change" OR "climate effect" OR "aviation-induced climate effect" OR "climate variation" OR "anthropogenic climate change" OR "net effect" OR "non-CO_2 impact" OR "global warming" OR "global warming potential" OR GWP OR "warming potential" OR "net surface warming" OR "global temperature-change potential" OR "temperature change" OR GTP</td><td>147</td><td rowspan="3">277</td><td rowspan="3">Contrail</td></tr>
<tr><td>AND
reduction OR mitigation OR "climate action" OR "emission control" OR "emission reduction" OR "CO_2 removal" OR "carbon dioxide removal" OR "GHG removal" OR "greenhouse gas removal" OR "net zero" OR "climate neutrality" OR "carbon neutrality"</td><td>144</td></tr>
<tr><td>AND
"Alternative fuel" OR "carbon neutral fuel" OR "fuel efficiency" OR SAF OR "sustainable aviation fuel" OR "H_2" OR hydrogen OR "liquid hydrogen" OR re-route*</td><td>43</td></tr>
</table>

		AND Forcing* OR "net forcing*" OR "radiative forcing*" OR "effective radiative forcing*" OR "atmospheric radiation*" OR "atmospheric forcing*" OR "climate forcing*" OR "non-CO_2 forcing*"	145		
	AND "non-CO_2* emission" OR "non-CO_2*" OR "anthropogenic warming emission" OR "long-lived GHG" OR "precursor emission" OR "precursor gas"	AND "climate change" OR "climate effect" OR "aviation-induced climate effect" OR "climate variation" OR "anthropogenic climate change" OR "net effect" OR "non-CO_2 impact" OR "global warming" OR "global warming potential" OR GWP OR "warming potential" OR "net surface warming" OR "global temperature-change potential" OR "temperature change" OR GTP	63	50	Non-CO2
		AND reduction OR mitigation OR "climate action" OR "emission control" OR "emission reduction" OR "CO_2 removal" OR "carbon dioxide removal" OR "GHG removal" OR "greenhouse gas removal" OR "net zero" OR "climate neutrality" OR "carbon neutrality"	74		
		AND "Alternative fuel" OR "carbon neutral fuel" OR "fuel efficiency" OR SAF OR "sustainable aviation fuel" OR "H_2" OR hydrogen OR "liquid hydrogen" OR re-route*	23		
		AND Forcing* OR "net forcing*" OR "radiative forcing*" OR "effective radiative forcing*" OR "atmospheric radiation*" OR "atmospheric forcing*" OR "climate forcing*" OR "non-CO_2 forcing*"	31		
aviation OR aircraft OR "air traffic" OR "air transportation"	AND Metric OR "climate change metric" OR "emission metric"	AND "non-CO_2* emission" OR "non-CO_2*" OR "anthropogenic warming emission" OR "long-lived GHG" OR "precursor emission" OR "precursor gas"	16	104	Metrics
		AND Contrail OR "contrail cirrus" OR cirrus OR "contrail overlapping" OR "contrail-contrail overlapping" OR "linear contrails" OR "persistent contrail" OR "short-lived contrail" OR "long-lived contrail" OR "cirrus cloud" OR "aviation-induced contrail cirrus"	28		
		AND "climate change" OR "climate effect" OR "aviation-induced climate effect" OR "climate variation" OR "anthropogenic climate change" OR "net effect" OR "non-CO_2 impact" OR "global warming" OR "global warming potential" OR GWP OR "warming potential" OR "net surface warming" OR "global temperature-change potential" OR "temperature change" OR GTP	107		
		AND NOx OR "nitrogen oxide emission" OR "nitrogen oxides*"OR " net NOx"	50		

	AND NOx OR "nitrogen oxide emission" OR "nitrogen oxides*"OR " net NOx"	AND "climate change" OR "climate effect" OR "aviation-induced climate effect" OR "climate variation" OR "anthropogenic climate change" OR "net effect" OR "non-CO_2 impact" OR "global warming" OR "global warming potential" OR GWP OR "warming potential" OR "net surface warming" OR "global temperature-change potential" OR "temperature change" OR GTP	152	285	NO_X
		AND "Alternative fuel" OR "carbon neutral fuel" OR "fuel efficiency" OR SAF OR "sustainable aviation fuel" OR "H_2" OR hydrogen OR "liquid hydrogen" OR re-route*	205		
		AND Forcing* OR "net forcing*" OR "radiative forcing*" OR "effective radiative forcing*" OR "atmospheric radiation*" OR "atmospheric forcing*" OR "climate forcing*" OR "non-CO_2 forcing*"	63		



(a)



(b)

Distribution of Searched Academic Papers Over the Years (2013-2023): (a) All searched academic documents; (b) Searched Academic documents rated 3 and above.

Step 2: Screening based on abstracts

A further screening through the review of abstracts was required for the 728 documents to identify the documents that are important and relevant to this project. The process involved reviewing the papers' abstracts, identifying the main topics (contrails, NOx, and metrics) covered by the papers, rating the papers' importance/relevance on a scale of 0 to 5, agreed with the DfT, and providing comments on the key findings that may be useful for the project report.

Four reviewers collaborated on this process. To keep the rating consistent amongst them, 20 documents (5 from each topic) were selected from the initial list for comparison review and rating calibration.

Paper's importance and relevance scale

Scale	Relevance/Importance to this project	Usefulness for the report writing
5	Very High	Extremely useful
4	High	Very useful
3	Moderate	Moderately useful
2	Low	Somewhat useful
1	Very Low	Not useful
0	Not relevant at all	(suggest deleting this paper)

Abstract review: Importance/Relevance Score of the Initial Search Results

Step 3: Establishing the project-specific literature database.

The review & rating results are demonstrated below.

Importance/Relevance Score	Number of papers			
	Contrail	non-CO2	Metric	NOx
5	21	3	7	19
4.5	1	0	1	2
4	74	11	20	72
3.5	16	0	0	4

3	75	14	27	84
2.5	2	1	2	6
2	44	8	15	48
1.5	0	0	0	0
1	33	1	2	26
0.5	0	0	0	0
0	11	12	30	24
Total	**277**	**50**	**104**	**285**

The scored literature were then grouped into the following categories to prioritise review:

- Literature rated 4.5 or higher: critical literature and must-read
- Literature with a score between 3 and 4.5: quickly review abstracts and reviewers' comments for relevance.
- Literature with a score between 2 and 3: may be included only if they have been influential in the field, based on experts' knowledge.
- Literature rated 1 or lower was excluded from the project-specific literature database due to its lower relevance to this project and its less usefulness for report writing.

Due to time-constraints, it was not possible to review all of the above papers. Expert knowledge was used to include other pieces of research (e.g. conference presentations and papers) not identified in the above process.

Search strategy – non-academic literature

The same search terms were used to identify publicly available literature from non-academic sources using multiple search engines and directly within different organisations own websites. Sources and databases associated with diverse range of stakeholders of aviation sector, e.g., NGOs, government groups, government agencies, industry associations, consultancy, research institutes, were identified.

Stakeholder engagement

In parallel to the literature being identified and prioritised, a workshop was held to understand the implications from and for the industry, align stakeholder expectations, and harness collective insights towards identifying key considerations for non-CO_2 aviation emissions metrics, policies, and implementation strategies. The workshop lasted for 3 hours and included representatives from across the industry, including airlines, pilots, ANSPs, engine manufacturers, sustainable fuel producers, pilots' groups, investors and solutions providers. The workshop provided an understanding of industry requirements, insights into perspectives on metrics, areas of common misperceptions, and actionable insights towards reducing non-CO_2 aviation impacts. The documented outcomes were intended to feed into academic research and policy frameworks, fostering collaboration and informed decision-making within the aviation sector. Findings from the stakeholder engagement can be found throughout the report in the sections entitled “primary research outputs”.

Stakeholder engagement included participant identification (including airlines, manufacturers, regulators, ANSPs, pilots and technology providers), preparatory communication (including, background documents on non-CO_2 aviation impacts, current research, and key discussion points), workshop structure including plenary discussions and breakout activities and utilisation of Miro Board for collaborative working.

Workshop agenda

The workshop covered the following items:

- **Introductions and Project Overview**: Facilitators set the context, introduced objectives, and clarified the role of stakeholders in shaping policy and metric considerations.
- **Technical Overview and Understanding of Attendees' Knowledge:** KPMG provided an overview of non-CO_2 impacts, addressing challenges and current activities, ensuring a baseline understanding among attendees.
- **Considerations on Applicable Metrics for Non-CO_2 Impacts:** Facilitated discussions on existing metrics and methodologies emphasised industry perspectives and explored consensus and divergence.
- **Discussion on Delivering Reductions in Non-CO_2 Impacts:** Breakout groups engaged in focused discussions on required changes, practical strategies, policy measures, and incentives.
- **Debrief and Conclusion:** Summarisation of discussions, sharing of group insights, closing thoughts from participants, and outlining the post-workshop follow-up plan took place.
- **Documentation:** Comprehensive documentation of workshop proceedings, discussions, ideas, and synthesised outputs from breakout sessions was compiled.
- **Post-Workshop Activities:**
    - Workshop outcomes were consolidated to shape academic research, future policy development, and industry implementation strategies.
    - Interviews were held with identified additional stakeholders (Met Office and MOD) to understand more on their role and activities in this space.

Appendix B: Primary research outputs

The debate around contrail management's scalability underlines the need for nuanced approaches to address the opportunity. Emphasising technological advancements and collaboration with meteorological offices can enhance data accuracy and advance emission reduction strategies.

Stakeholder	Decisions stakeholders need to make
All stakeholders	• Clarity on the duration and impact of contrails for focused actions. • Leveraging existing technologies for immediate emissions reduction. • Rectifying misconceptions about fuel burn and encouraging environmentally optimised flight planning. • Robust verification tools for data accuracy, especially for contrails and weather forecasts. • Collaboration and knowledge sharing across industries, including insights from the military sector. • Common language development for effective communication between academic, aviation, and other stakeholders. • Counterfactual analysis for evaluating alternative outcomes and influencing policymakers.
Government Bodies	• Comprehensive guidance on emission reduction strategies. • Clear parameters and aligned incentives for emission reduction. • Early policy interventions to address airspace complexities and incentivise key investments. • Regulatory frameworks recognising and incentivising actors' movements for sustainable aviation.
Airlines/Industry Players	• Specifics on contrail impacts of different flight types. • Technological advancements, especially in aircraft instrumentation for better emission data. • Clarity on emerging regulations and incentives for informed decision-making. • Consistent agreed metric for reporting purposes at national and international levels.
Meteorological Offices	• Collaboration on contrails, weather data, and non-CO_2 impacts.
Air Navigation Service Provider (ANSP)	• Data on contrails and air traffic for effective navigation

Aircraft Manufacturers	• Insights into aircraft design for emission reduction
Aircraft Operators (Including Airline Groups)	• Operational data for optimising flight routes and fuel efficiency
Airline Lenders and Leasing	• Financial considerations for sustainable aviation investments.
Airports	• Emission data and infrastructure support for sustainable aviation
Engine Manufacturers	• Technological advancements for fuel-efficient engines
Solutions Providers	• Innovative solutions for emission reduction
Fuel Providers (Including Sustainable Fuel Producers)	• Sustainable fuel options and compatibility with existing infrastructure. • Information on sustainable fuel production, availability, and related projects
Neighbouring Airspace	• Coordination on cross-border aviation emissions and strategies.
Regulators	• Emerging regulations and compliance requirements.
Trade Associations/Bodies	• Industry insights, collective strategies, and support for initiatives

Appendix C: Overview of Requirement from the Department for Transport

The project is comprised of two parts, the first is to undertake a literature review of all existing research on aviation's non-CO_2 impacts and the second is to carry out an evaluation of the existing methodologies and metrics to measure and monitor the non-CO_2 impacts of aviation.

Literature review of aviation's non-CO_2 impacts

There is a significant body of academic literature in existence on aviation's non-CO_2 impacts and a lot of work is ongoing in the UK and internationally. A literature review will consolidate the existing research in this area, the key findings to date and identify where further research may be required, and how this could be most effectively implemented.

A key driver of this review is to ensure that any future research into aviation's non-CO_2 impacts supported by the Government avoids unnecessary duplication of work already in existence.

Evaluation of the existing methodologies to measure the non-CO_2 impacts of aviation

Whilst multiple climate/ CO_2-e metrics exist to account for aviation's non-CO_2 impacts, there is currently a lack of consensus over the correct methodology to quantify aviation's non-CO_2 impacts and how to compare them to CO_2 emissions to account for aviation's full climate impact. This scientific uncertainty makes accurately monitoring and measuring the non- CO_2 impacts of aviation challenging.

This analysis will identify, compare and evaluate all existing non-CO_2 methodologies/climate metrics relating to the non-CO_2 impacts of aviation, and methods for comparing them to CO_2 emissions. The intention is for the evaluation to identify which, if any, is most appropriate to use. If the analysis concludes that an alternative method is required, the report should make a recommendation on what a new bespoke methodology could include and what additional work might be required to develop it.

The following are not in scope:

- Research literature about aviation's CO_2 impacts, unless it is referenced when comparing those of non-CO_2.
- Non-CO_2 literature and methodologies that are not in relation to aviation emissions and impacts.

Detailed requirements

DfT expects the project to commence with a discussion on the scope, methodology, drafting of products and timings of meetings once the contract has been awarded.

The Supplier must have the expertise, skills, and capabilities to undertake the project, including a good understanding of aviation, non-CO_2 impacts of aviation and climate metrics.

The analysis will inform the approach to a wider non-CO_2 research programme and will be considered in policy development to address aviation's non-CO_2 impacts.

The Supplier will be required to hold a dissemination event to maximise exposure to the publication of the project outcomes.

The project outputs for the Literature review of aviation's non-CO_2 impacts are as follows:

A review of non-CO_2 academic literature to ensure the Government has a balanced view of the current scientific understanding of aviation's non-CO_2 impacts and potential mitigations on a global level. The literature review will seek to establish answers to the following questions from each of the individual research papers:

The Requirement:

i) What are the non-CO_2 impacts from aviation and how do they affect the climate?

ii) How significant are these non-CO_2 impacts when compared to CO_2 emissions?

iii) What mitigation measures have been explored to address aviation's non-CO_2 impacts and what are the pros and cons of each of these measures?

iv) What knowledge gaps have been identified that require further research?

A review of previous, current, and upcoming research projects/programmes from government, academia and industry taking place both within the UK and internationally exploring aviation's non-CO_2 impacts, to highlight the research gaps as well as help the Government to avoid any duplication of research.

Recommendations on what further research is required in this space based on the findings.

The project outputs for the Evaluation of the existing methodologies to measure the non-CO_2 impacts of aviation are as follows:

Identification and evaluation of all internationally known climate metrics for measuring aviation's non-CO_2 impacts.

A comparison of the pros and cons of all existing climate/ CO_2-e metrics to measure the non-CO_2 impacts of aviation (particularly for NOx and contrails) and how non-CO_2 could be compared to CO_2.

An evaluation of potential ways to measure the non-CO_2 impacts of individual flights.

Recommendations on which metric is most fit for purpose for policy use based on the findings. If the evaluation finds that none of the existing metrics are appropriate for policy design, the Supplier is to set out an alternative approach for measuring non-CO_2 impacts and comparing them to CO_2.

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