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AIR QUALITY AND CLIMATE IMPACTS INTERDEPENDENCIES AND TRADE-OFFS OF AVIATION EMISSIONS

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CAEP IMPACTS AND SCIENCE GROUP (ISG)- AIR QUALITY AND CLIMATE IMPACTS INTER-DEPENDENCIES AND TRADE-OFFS OF AVIATION EMISSIONS

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SUMMARY

- The climate impact of aviation today primarily stems from emissions of carbon dioxide (CO_2), and contrail-cirrus formation, while the air quality impacts are mainly due to aviation emissions of oxides of nitrogen (NO_x) and non-volatile particulate matter (nvPM). Other emissions such as water vapour (H_2O) and oxides of sulphur (SO_x) also contribute to aviation related environmental impacts but are thought to have smaller impacts.

- The solution space to minimize aviation environmental impacts consists of more efficient aircraft and engines to reduce their fuel consumption, improved combustion technologies to reduce NO_x and nvPM emissions, new alternate fuels or energy carriers to minimize CO_2 as well as nvPM and SO_x emissions and operational mitigations to improve fuel efficiency and avoid or reduce formation of contrails having significant radiative effects (see "CAEP Impacts and Science Group (ISG) – Contrail Science Workshop Report (Lee et al. 2025)." for more details on contrails). This report does not consider the indirect effects (e.g., from airport and ground vehicles) on the environment and the focus is on the interdependencies between air quality and climate impacts of aircraft.

- The climate impacts of aviation emissions of CO_2 (including the lifecycle emissions) have high certainty and have therefore been the focus of several industry and government targets. While there is scientific uncertainty in the relative magnitude of impact that stems from various aviation emissions components, the literature suggests that climate impacts of non-CO_2 components of aviation emissions are comparable to that of CO_2 emissions from aviation. Recent research has focused on the complex interactions between SO_x, NO_x, and soot emissions with background aerosols and the different pathways through which they contribute to the radiative budget.

- CO_2 effects last over centuries while non-CO_2 impacts are short-lived and highly dependent on emission location and timing. In order to capture these varying lifetimes of different components of aviation emissions and the time scale of the resulting climate impact several "climate metrics" are in common use in the literature. The impact

metrics in use span a large range from the instantaneous radiative forcing to integrated emission metrics such as the global warming potential over a certain time horizon to monetized economic damages. The choice of metric is ultimately a value judgement as different metrics are useful under different situations and the specific questions to be answered.

- The net present-day radiative effect of aircraft NO_x emissions is estimated to be positive. However, this estimate does not account for the cooling from NO_x attributable to aerosols. These effects are associated with large uncertainties and their inclusion reduces the net NO_x radiative forcing. As a consequence of these indirect forcings, and the future scenario for background concentrations of ozone precursors, recent studies suggest that the sign of the future net NO_x radiative forcing could vary from positive to negative. Further research to better understand the net NO_x radiative forcing is needed.

- The net aviation aerosol direct radiation interaction is assessed to be negative because of the dominance of the cooling influence of sulphate aerosol, and to a lesser extent nitrate aerosol, over the warming influence of soot. Sulphate and soot emissions can also interact with low and high-level clouds and these climate impacts remain highly uncertain both in terms of sign and magnitude

- Aviation emissions contribute to degradation of air quality via increase in ground level concentrations of harmful pollutants. Recent research has strengthened the understanding that aviation air quality impacts include both local-to-regional scale impacts due to near-surface (i.e., near airport) emissions as well as global scale impacts resulting from emissions during cruise.

- Although air quality impacts per unit of fuel burn are greater from landing and take-off emissions, the fact that over 90% of aviation fuel burn occurs above 3,000 ft means that cruise emissions could dominate overall impacts on air quality. According to some modelling studies, these global air quality impacts are principally due to cruise-altitude emissions of NO_x. In addition to the global air quality impacts, aircraft emissions during the LTO phase also have been shown to cause health impacts due to exposures to ultrafine particles (UFP), $PM_{2.5}$, O_3 and NO_2 concentrations. Most national air quality standards have historically focused on near airport emissions.

- While advances in aircraft technology can lower fuel burn and CO_2 emissions, certain design choices can lead to increased NO_x emissions due to an increase in combustor temperatures. This creates a challenge for balancing the environmental impacts of CO_2, which predominantly affects climate change, and NO_x, which impacts both climate and air quality.

- Monetizing the environmental costs (i.e., combined climate and air quality impacts) is one potential way to quantify the disparate impacts on a common basis and understand the trade-offs between CO_2 and NO_x emissions reducing technology. Such metrics are still subject to strong limitations and introduces further assumptions and uncertainties in how various impacts (climate, health, premature mortalities) are valued but can guide design decisions, such as small increases in fuel burn in exchange for larger NO_x reductions, particularly as more sustainable aviation fuels (SAFs) are introduced. However, trade-offs between non-volatile particulate matter (nvPM) and NO_x are less understood, with emissions impacts highly dependent on specific engine technologies.

- Future technological advancements, combined with SAF scale-up and deployment, are expected to play a critical role in reducing aviation's environmental footprint in the medium to long term. However, many of these technologies (such as hydrogen aircraft) that are thought to have benefits are at very low Technology Readiness Levels (TRLs) with several open questions (e.g., contrail impacts for hydrogen combustion are unknown for example – See "CAEP– Contrail Science Workshop Report). Achieving meaningful reductions in emissions (especially in the near-term) also requires addressing inefficiencies in air traffic management which, if left unaddressed, can undermine the gains from technological improvements.

INTRODUCTION

Aviation plays a crucial role in connecting people, facilitating knowledge exchange, driving innovation, and enabling global trade and tourism. However, aviation emissions are also known to contribute to climate and air quality impacts (Barrett, Britter, and Waitz 2010; Brasseur et al. 1998, 2016; Brasseur, Müller, and Granier 1996; Lee et al. 2021). The climate impact of aviation primarily stems from emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_x), contrail-cirrus formation (being dependent on emissions of water vapour (H_2O) and non-volatile particulate matter (nvPM)) with smaller contributions from oxides of sulphur (SO_x) as well as additional climate impacts of H_2O and nvPM emissions. The metric chosen to quantify the climate impact influences the magnitude and relative contribution of each of these species (Grobler et al. 2019; Lee et al. 2021). The air quality impacts of aviation are primarily driven by emissions of NO_x, SO_x, and nvPM (Barrett et al. 2010; Eastham et al. 2024; Yim et al. 2015). These impacts arise from both local near-ground emissions during take-off and landing and high-altitude emissions (Arter et al. 2022; Barrett et al. 2010; Eastham et al. 2024; Lee et al. 2013).

There are several research groups and research publications that have focused on solutions to mitigate the climate and air quality impacts of aviation. These can be broadly classified into three approaches to mitigating the environmental impacts of aviation. The first approach involves the use of low greenhouse gas (GHG) fuels, such as Sustainable Aviation Fuels (SAFs), to address CO_2 emissions (Huq et al. 2021; Staples et al. 2014; Wang et al. 2021). The second approach focuses on operational strategies to reduce aviation attributable climate impacts (Gao 2013; Gierens, Lim, and Eleftheratos 2008; Grewe et al. 2014; Linke, Grewe, and Gollnick 2017; Teoh et al. 2020; Zengerling et al. 2023) one such example (amongst others) is operational strategies and tactics to reduce aviation contrail impacts (further details specifically on contrail avoidance available in "CAEP Contrail Science Workshop Report"). The third approach utilizes technological innovations to reduce NO_x and nvPM to mitigate air quality impacts and to reduce CO_2 to mitigate climate impacts (Cumpsty et al. 2019; also refer to ICAO Doc 10127).

There are known interdependencies between the climate and air quality impacts of aviation. For instance, SO_x emissions lead to the formation of sulphate aerosols, which can exert a negative radiative forcing by reflecting incoming solar radiation and thereby cooling the planet (Brasseur et al. 2016; Grobler et al. 2019; Prashanth et al. 2022). However, SO_x emissions also contribute to an increase in particulate matter ($PM_{2.5}$), which has adverse effects on human health (Burnett et al. 2014; Dockery et al. 1993). Additionally, while certain technology solutions can result in a reduction in climate and air quality impacts (e.g., increasing the component efficiencies of a gas turbine can reduce both CO_2 and NO_x emissions) other technological solutions to reduce climate impacts may inadvertently increase air quality impacts (e.g., using a higher compressor pressure ratio in a gas turbine to reduce CO_2 emissions, while beneficial for climate, can result in higher NO_x emissions for the same combustor technology due to an increase in combustor inlet temperature, which negatively impacts air quality).

In the following sections, we summarize the state of the science on these topics, based on a literature review of peer-reviewed publications. Section 1 will explore the pathways through which aviation emissions affect the climate and the various metrics used in scientific literature to quantify these impacts. Section 2 will delve into the chemical processes responsible for aviation's air quality impacts and discuss methodologies for quantifying the associated health impacts. Section 3 will provide an extensive discussion of mitigation strategies, and in Section 4, we will examine the interdependencies between climate and air quality impacts of aviation arising from several sources.

1. CLIMATE IMPACTS OF AVIATION

Aviation contributes to the global climate warming. Aircraft emissions affect atmospheric composition and modify the cloudiness, which in turn influence the radiative balance of the atmosphere (**Figure 1**). The present contribution of aviation to global CO_2 emissions is around 2.4% (Lee et al. 2021). Global aviation fuel use and CO_2 emissions have increased in the last four decades and are anticipated to grow, with the largest growth coming from Asia (Lee et al. 2021). The growth in air traffic results in an increase in the CO_2 contribution to the warming (Boucher et al. 2021; Klöwer et al. 2021; Terrenoire et al. 2019). In addition to CO_2, other species emitted by aviation ("non-CO_2" emissions) also impact the global climate. Collectively aviation CO_2 and non-CO_2 emissions are calculated to represent about 3.5% (on an effective radiative forcing basis; defined below) of the total anthropogenic radiative impact on climate in 2011 (Lee et al. 2021), but further increase in air traffic as projected (Dray et al. 2022) combined with clearer paths to decarbonization in other sectors may increase the absolute and relative contribution (Cames et al. 2015) of aviation to global climate change even with further technological and operational efficiency increases (Grewe et al. 2021).

Quantified on an Effective Radiative Forcing (ERF) basis, the CO_2 and non-CO_2 related impacts account for about one-third and two-thirds of aviation's total climate impact respectively (Lee et al. 2021). However, the relative contribution of aviation's CO_2 and non-CO_2 impacts might change in the future as the non-CO_2 impacts are dependent on the background atmosphere and contingent on the rate of growth of aviation (Brazzola, Patt, and Wohland 2022; Klöwer et al. 2021). In addition, aerosol-cloud interactions are not yet considered in the aviation ERF evaluation but could significantly change the non-CO_2 contribution for the present-day and in the future. When aviation's climate impacts are quantified in terms of the integrated future contribution to global warming (over a 100 year time-horizon) due to a unit of fuel burned the contribution of aviation CO_2 emissions account one-half to two-thirds of the total aviation attributable climate impact (Grobler et al. 2019; Lee et al. 2021). The non-CO_2 impacts of aviation have a greater uncertainty associated with them compared to that from CO_2. Additionally, non-CO_2 and CO_2 emissions have very different atmospheric lifetimes and therefore the *resulting radiative forcing* from these species differ substantially in time scales. CO_2 remains in the atmosphere for millennia, whereas non-CO_2 components are short-lived, persisting for hours, months, or years. Consequently, long-lived gases such as CO_2 are considered "well-mixed" and the climate impact of CO_2 is effectively independent of emission location, while the radiative forcing from non-CO_2 components are highly dependent on the location and time of emissions.

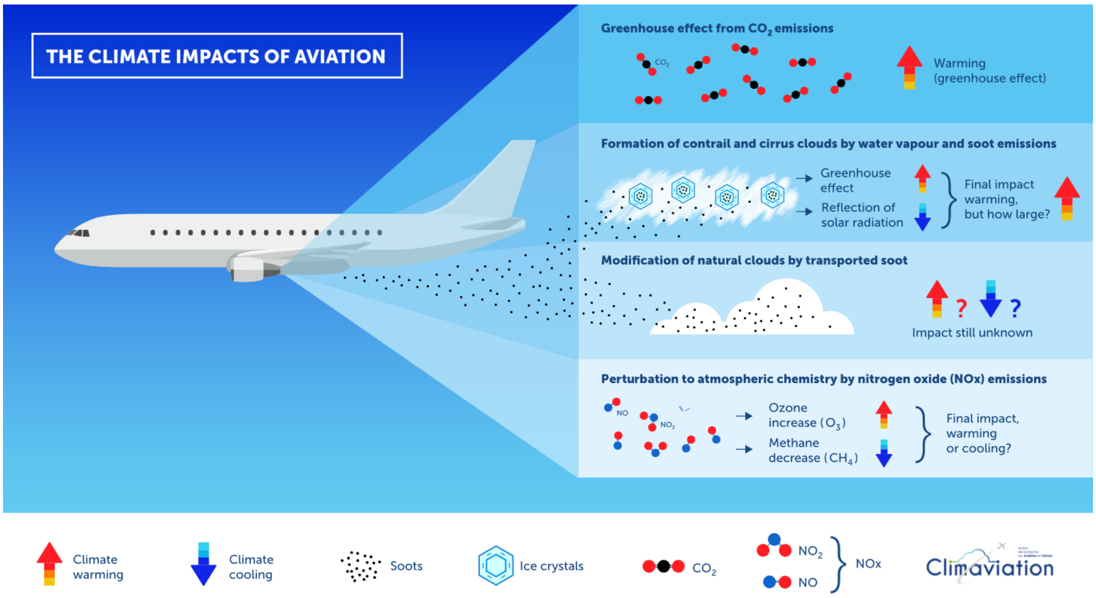

Figure 1. Schematic overview of the processes by which aviation emissions and increased cirrus cloudiness affect the climate system. Courtesy: N. Bellouin, G. Dannet (ClimAviation).

Climate metrics

The most common measure used to quantify the climate effects of aviation is the Radiative Forcing (RF) which has units of Watts per square meter ($W.m^{-2}$). It characterizes the instantaneous size of the perturbation to the planetary radiation budget relative to the pre-industrialization period. The perturbation in the radiative balance (i.e., the RF) of the earth-energy system leads to a surface temperature change (a positive RF leads to a warming, and a negative RF to a cooling). Recent IPCC assessment have adopted the ERF as the preferred measure (Forster and Storelvmo 2023; Myhre et al. 2013). ERFs include the instantaneous forcing following adjustments in both tropospheric and stratospheric temperatures, water vapour, clouds, and some surface properties (Forster and Storelvmo 2023). For some climate change forcers (e.g., CO_2), the difference between RF and ERF is small; for others (e.g., aerosols, contrails) it is substantial (Ponater et al. 2021), and a source of additional uncertainty (Lee et al. 2021). RFs and ERFs can be used to calculate several climate metrics relevant to different policy targets and for different time horizons. A frequently used approach is to quantify the climate impact of a species relative to the climate impact of CO_2 in the same time frame (abbreviated as CO_2-eq or CO_2e). As part of the Paris Agreement Rulebook, the Global Warming Potential with a 100-year time-horizon (GWP_{100}) was decided as the default metric to report aggregated emissions and removals of greenhouse gases. However, no specific metric has been formally adopted for the aviation sector (Fuglestvedt et al., 2023). In particular, for short-lived emissions other metrics may be more relevant in certain contexts (Allen et al. 2022; Collins et al. 2020; Lund et al. 2017). Several other metrics have been proposed for quantifying the climate impact in the literature and the recent analysis by Megill, Deck, and Grewe (2024) suggests that there are derivative and alternative metrics that outperform the GWP in the case aviation non-CO_2 climate impacts. **Table 1** below summarizes the key climate metrics that are currently in use in literature.

Table 1. Prevalent metrics use in the scientific literature. In the equivalency (or CO_2-e) metrics below the choice of the time horizon i, is primarily a value judgement. Recent work in the literature compares and contrasts the benefits and limitations of different metrics for use in determining aviation emissions equivalence (Megill, Deck, and Grewe 2024).

	Metric	**Units**	**Description**	**Notes and caveats**
Physical metrics or climate indicators	Radiative Forcing (RF)	[W/m^2]	Global Instantaneous perturbation in the net radiative flux at the top of the atmosphere (excludes any adjustments).	• Most directly calculated from the emissions with least uncertainty. • Does not capture the response of atmosphere or the Earth system. • As an instantaneous metric it does not capture the lifetime of the associated emissions/ species and the resulting impact. • Does not capture spatial inhomogeneity of forcers well.
	Stratospheric adjusted Radiative Forcing (SARF)	[W/m^2]	The global perturbation in net radiative flux at the top of the atmosphere *after* accounting for the stratosphere to reach radiative equilibrium.	• Most often used historically. • Does not capture the response of the troposphere or the Earth system.
	Effective radiative forcing (ERF)	[W/m^2]	The global perturbation in net radiative flux at the top of the atmosphere *after* accounting for *rapid adjustments* excluding radiative responses of the surface temperature change.	• Widely considered as a better representation of the radiative impact by including the rapid adjustments (cloud cover in particular) to be “effectively” part of the RF itself. • Requires the use of a comprehensive climate model to calculate the *efficacies*. • Scientific uncertainties remain in key aspects such as aerosol-cloud interactions. • Not conducive to compare climate impacts of components that have very different atmospheric lifetimes.
	Temperature change	[K]	The global resultant mean surface air temperature change due to the perturbation.	• Requires the use of a comprehensive climate model capturing key climate feedbacks or at least an emulator. • Not conducive to compare forcers with significant spatial heterogeneity.

Emission metrics	Global Warming Potential (GWP_i)	[CO_2-eq]	RF due to a pulse emission of a given component integrated over a time horizon i, relative to a pulse emission of an equal mass of CO_2	• The choice of the time horizon i, is inherently a value judgement as it depends on the relative importance of short- and long-term impacts. • Primarily suitable for well mixed greenhouse gases.
	Efficacy weighted Global Warming Potential ($EGWP_i$)	[CO_2-eq]	Similar to GWP but weighted by the efficacy of the species or component of interest	• Recently proposed to better match and track mean or peak temperature-based climate indicators • Highly uncertain particularly for short-lived forcers such as contrails
	Global Temperature change Potential (GTP_i)	[CO_2-eq]	Change in global mean surface temperature at a particular point in time i due to a given component, relative to that of CO_2.	• The choice of the time horizon i, is inherently a value judgement as it depends on the relative importance of short- and long-term impacts. • Unlike GWP, GTP is an end-point metric – change in temperature at a particular future assessment time, integrated versions of this (iGTP) also are in use.
	Average Temperature Response ratio (ATR_i)	[K]	The average change in temperature over a given time horizon i. Time horizon initially proposed to account for the operation lifetime of an aircraft.	• Effectively the absolute GTP normalized by the time horizon of choice. • Historically proposed for aircraft design • Requires the calculation of the global mean temperature change first
Economic metrics	Monetised damages	[$] or [€]	The estimated economic impact due to climate change attributable to a particular component using damage functions.	• Allows for comparison of climate impacts with other aspects of environmental impacts (e.g., air quality, noise) on a common basis making it policy relevant • Use of a discount rate inherently introduces a value judgement of near- vs long-term impacts • Statistical valuation (in monetary units) of climate damages (e.g., using integrated assessment model results) and health impacts (e.g., using values of statistical life) and climate introduce further assumptions and uncertainties.

As an example for illustrating the complexity issue arising from the choice of a climate metric, **Figure 2** shows the impact of using different metrics while evaluating the climate impact of NO_x emissions calculated as the ratio of the total (CO_2 + NO_x) to the CO_2 only climate impact of aviation emissions. The ERFs illustrate that the total (CO_2 + NO_x) effect is 43% greater than that of CO_2 alone. The GWP_{20}, which integrates the radiative forcing over a 20-year time-horizon, shows that the effect of NO_x (dominated by the short-term O_3 forcing at this time-horizon) results in CO_2-equivalent emissions that are larger than just CO_2 emissions by 76%. The commonly adopted GWP_{100} results in an CO_2-equivalent total emission larger than CO_2 emissions alone by only 16% because the long-term cooling effect associated with CH_4 comes into play at this time horizon. When accounting for the climate system inertia, the GTP_{20} metric, the climate response of aviation NO_x becomes dominated by the CH_4 long-term cooling, resulting in a total CO_2-equivalent emission reduction of 16%. This reduction is progressively reduced for the GTP_{50} and further for the GTP_{100} since the CH_4 lifetime remains relatively short compared to CO_2. In the case of the ATR_{100} metric, averaging the temperature increase over 100-year period, the increased effect of aircraft NO_x equivalent emissions above CO_2-only emissions is 19%. The above comparison of the different metrics is useful to illustrate how the magnitude of the impact that is calculated varies as different metrics differently weight the short term and long-term impacts. However, it should be emphasized that these metrics are not interchangeable and the relevance of a particular metric to a use case needs to be carefully considered in the light of the context and question being asked. It should be further pointed out that the attribution methods used to determine the aviation contribution to climate change is also subject to discussion.

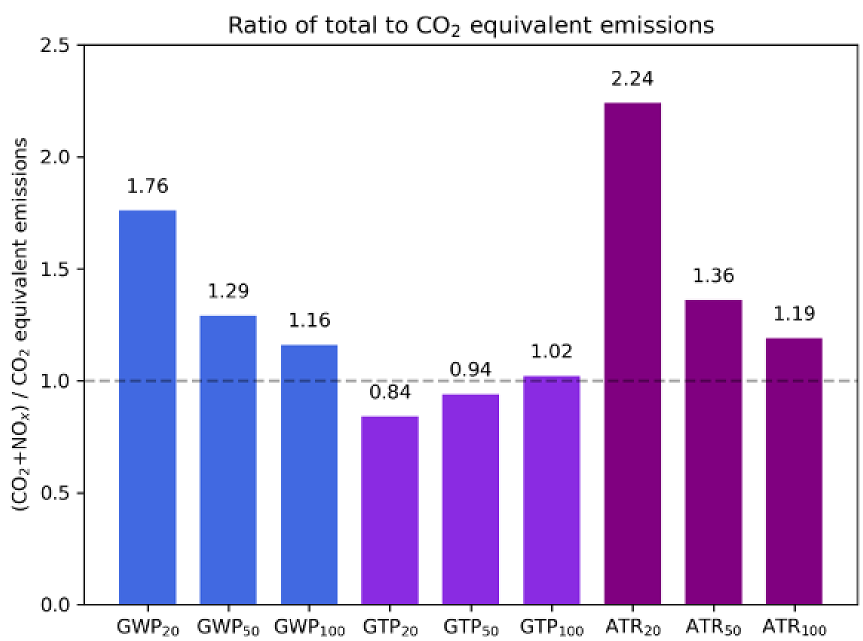

Figure 2. Ratio of the total (CO_2 + NO_x) to CO_2 only equivalent emissions calculated using different metrics (ERF, GWP, GWP, GTP, ATR) and time-horizons. ERF, GWP, GTP and ATR calculated by the authors based on radiative forcings from Terrenoire et al. (2022) and the impulse response model in Hauglustaine et al. (2022).

Non-CO_2 effects

The non-CO_2 emissions directly emitted by the aircraft and relevant for climate impact purpose include water vapour, soot, SO_x, and NO_x (**Figure 1**). Whereas the direct radiative forcing of water vapour emissions is currently assessed to be small and positive (Lee et al. 2021), it is highly dependent on the altitude of the emissions and its importance increases when emitted higher into the stratosphere (Eastham et al. 2022; Zhang et al. 2021). Emissions of SO_x arising from sulphur in the fuel, which is oxidized to form sulphate particles, results in a negative (direct) ERF. Emissions of soot particles result in a (direct) positive ERF. Recent research has focused on the complex interactions between SO_x, NO_x, and soot emissions with background aerosols and the different pathways through which they contribute to the radiative budget (**Figure 3**). The net aviation aerosol-radiation interaction is assessed to be negative because of the dominance of the cooling influence of sulphate aerosol, and to a lesser extent nitrate aerosol, over the warming influence of soot (Lee et al. 2021; Prashanth et al. 2022; Terrenoire et al. 2022) and that is estimated to not change under future scenarios (Terrenoire et al. 2022). Sulphate and soot emissions can also interact with low and high-level clouds (both natural and aviation induced), respectively; however, these climate impacts remain highly uncertain both in terms of sign and magnitude (Lee et al. 2021; Righi, Hendricks, and Brinkop 2023). The modelled indirect aerosol-cloud interactions are highly parametrized and strongly dependent on the assumed size of the emitted sulphate particles or ice nucleating abilities of soot. There are currently no best estimates of the magnitudes of these effects.

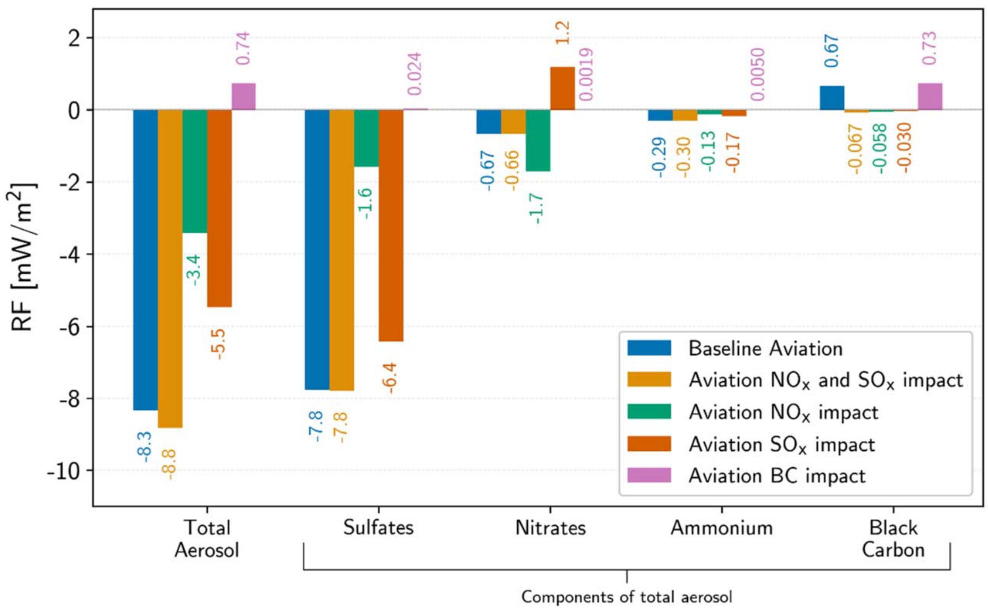

Figure 3. Aviation-attributable radiative forcing (in mW/m^2) due to aerosol species (total aerosol and its components—sulphates, nitrates, ammonium, soot (or black carbon)). Total tropospheric aerosol includes the RF due to other aerosols such as organic and black carbon (Prashanth et al. 2022). The sum of the fractional RF components from NO_x, SO_x and BC does not equal 1 due to non-linear interactions.

An important non-CO_2, non-contrail effect from aviation on climate, at present, is the changes in atmospheric chemistry due to emissions of NO_x. The net forcing of NO_x depends on the latitude, altitude, time of year of emission as well as the size of emission or background atmosphere (e.g., Köhler et al. 2013; Skowron et al. 2021; Søvde et al. 2014; Stevenson et al. 2004) and local weather conditions (Maruhashi et al. 2024). Aviation NO_x emissions contribute to climate change by formation of O_3 and destruction of atmospheric CH_4. Both O_3 and CH_4 are greenhouse gases, and these perturbations result in warming and cooling effects, respectively, and at different time- and geographical scales. The CH_4 reduction also has secondary effects that lead to further cooling: a decrease in background O_3 and a reduction in stratospheric water vapor (SWV). Whereas the total (net) present-day radiative effect of aircraft NO_x emissions is estimated to be positive (Lee et al. 2021) these estimates do not account for cooling from NO_x attributable aerosol. NO_x emissions are also involved in the direct increase of nitrate aerosols and indirect formation of sulphate aerosols, via increased hydroxyl radical (OH) and SO_2 conversion to particles (**Figure 3**). These effects are associated with large uncertainties and result in negative forcings (Prashanth et al. 2022; Terrenoire et al. 2022), and the inclusion of these processes reduces the net NO_x radiative forcing (Terrenoire et al. 2022). As a consequence of these indirect forcings, and also depending on the future background scenario for surface emissions of ozone precursors, recent studies suggest that the sign of the future net NO_x radiative forcing could vary from positive to negative, and it remains highly uncertain (Maruhashi et al. 2022; Skowron et al. 2021; Terrenoire et al. 2022).

In addition to the above gas phase and aerosol species, condensation of water vapour on nuclei results in the formation of ice crystals present in condensation trails (contrails) and contrail cirrus clouds. The radiative effect of contrail cirrus varies strongly (positive to negative RF) with location, altitude, and time of emissions. The net (day and night) RF of contrail cirrus is positive (Lee et al. 2021) leading to a warming of the climate system, but its impacts are associated with significant uncertainties (Kärcher 2018; Lee et al. 2021). Detailed discussions on the aviation induced cloudiness are presented in the CAEP Contrail science workshop report (Lee et al. 2025).

2. AIR QUALITY IMPACTS OF AVIATION

Aviation emissions contribute to air quality degradation via an increase in near-surface concentrations of harmful pollutants. The key pollutants are particulate matter with a diameter of less than 2.5 microns ($PM_{2.5}$) and ozone. Aviation can increase their concentrations both through direct emissions of harmful pollutants (e.g. ultrafine soot) and by emitting precursor pollutants (e.g. ozone forming as a result of aircraft NO_x emissions). The air quality impacts of aviation emissions are now understood to include both global impacts resulting principally from emissions during cruise, and local-to-regional impacts resulting from near-airport emissions (Barrett et al. 2010; Eastham et al. 2024; Eastham and Barrett 2016; Lee et al. 2013; Quadros, Snellen, and Dedoussi 2020). Air quality impacts, when monetized, may be comparable to the climate impacts of aviation (Grobler et al. 2019) but are subject to further uncertainties.

Global air quality

Based on results from several simulations, the degradation of global air quality by aviation is attributed principally to cruise-altitude emissions of NO_x (Barrett et al. 2010; Eastham et al. 2024; Yim et al. 2015). Although air quality impacts per unit of fuel burn are greater from landing and take-off emissions, the fact that over 90% of aviation fuel burn occurs above 3,000 ft (Simone, Stettler, and Barrett 2013) means that cruise emissions may dominate overall impacts on air quality (Grobler et al. 2019). The key contributor is found to be emissions of cruise-altitude NO_x in these studies (Barrett et al. 2010; Lee et al. 2013; Quadros et al. 2020). Although particulate matter emitted or formed at cruise altitude is rapidly washed out of the atmosphere before being transported to the surface (Whitt et al. 2011), the ozone formed by cruise NO_x is sufficiently insoluble and long-lived to travel to the surface (Eastham and Barrett 2016). Once at the surface ozone both constitutes a health risk in itself and accelerates the formation of harmful $PM_{2.5}$ from existing non-aviation precursor emissions (Eastham and Barrett 2016; Prashanth et al. 2022). The amount of $PM_{2.5}$ formed depends both on the region of emission and on the concentrations of precursor pollutants such as ammonia in impacted regions (Phoenix et al. 2019; Quadros et al. 2020). However multiple studies have shown that the contribution of aviation to changes in surface ozone and $PM_{2.5}$ is maximized during winter (Eastham and Barrett 2016; Lee et al. 2013; Phoenix et al. 2019).

Although the relative contribution of aviation to surface changes in air quality is small compared to other sectors (Dasadhikari et al. 2019; Phoenix et al. 2019), the additional ozone and $PM_{2.5}$ both result in public health impacts estimated to range from 10,000 to 74,000 premature mortalities per year (Barrett et al. 2010; Eastham et al. 2024; Eastham and Barrett 2016; Prashanth et al. 2021; Quadros et al. 2020; Yim et al. 2015). These totals are nonetheless subject to significant uncertainty. A multi-model estimate found broad agreement between models that surface concentrations of ozone and $PM_{2.5}$ are increased by full-flight aviation emissions (Cameron et al. 2017), and the individual components in the chain of effect from cruise NO_x emissions to health impact are individually well understood. However, aviation emissions typically cause increases which are spatially diffuse (Eastham and Barrett 2016) and on the order of 1-2% of background ozone and $PM_{2.5}$ (Hauglustaine and Koffi 2012; Lee et al. 2013). As a result, directly attributing observed changes in air quality to aviation emissions remains challenging.

Ongoing research has helped to reduce these uncertainties. For example, there had been disagreement regarding whether impacts calculated in older studies of aviation's air quality impacts (Barrett et al. 2010) were overestimated due to the use of low spatial resolution in the models. Although Yim et al., using a chain of nested models, had not found a significant reduction in aviation-related air pollution when using higher resolution models (Yim et al. 2015), Vennam et al. reported a 13-70 times reduction in estimated exposure when using a high-resolution, nested model compared to results from a lower-resolution, global model (Vennam et al. 2017). This result has recently been used to argue that surface level effects of cruise emissions are too uncertain to justify action (Lee et al. 2023). However, other studies found no such discrepancy, with similar air quality impacts at coarse and fine model resolutions (Quadros et al. 2020). Subsequent work has shown that the discrepancy reported by Vennam et al. is likely due to neglecting the effect that aviation has on the air entering at the boundaries of the United-States domain, meaning that the high-resolution component of Vennam et al. considered only near-surface emissions (Eastham et al. 2024). The Eastham et al. (2024) study also showed that $PM_{2.5}$ and ozone related global air quality impacts from aviation are almost entirely due to cruise-altitude NO_x emissions, rather than Landing and Take Off (LTO) emissions or non-volatile particulate matter, and that most air quality impacts from aviation within the US result from fuel burned outside of US air space (see **Figure 4**). The exception is exposure to nvPM which is mostly from local sources but makes up less than 1% of the population exposure to $PM_{2.5}$ attributable to aviation and is irrelevant to the ozone impacts. These findings add to the existing consensus between models showing a hemispheric-scale increase in air pollution associated with cruise-altitude emissions.

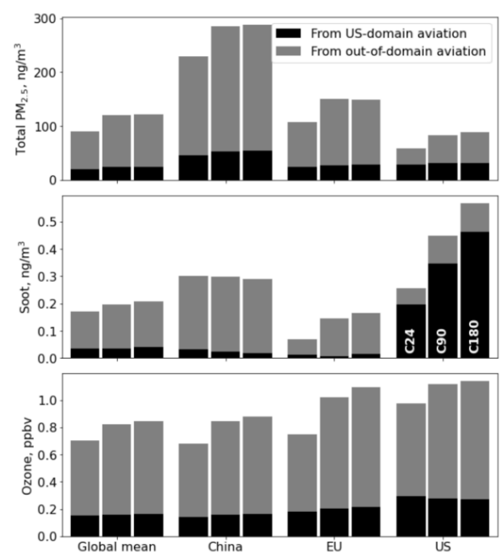

Figure 4. Estimated population-weighted mean exposure to $PM_{2.5}$ (top), soot (middle), and ozone (bottom) resulting from cruise altitude emissions for four different regions. Each group of vertical bars shows the estimated exposure in a different world region (i.e., a receptor region), and each individual bar shows the effect of increasing global model resolution from ~400 km (C24, left) to 100 km (C90, centre) and then 50 km (C180, right). The black segment of each bar shows the exposure resulting specifically from emissions over the contiguous US (in every group). Adapted from Figure 4 of Eastham et al. (2024).

Local air quality

In addition to the global air quality impacts, aircraft emissions during the LTO phase also have been shown to cause health impacts due to exposures to ultrafine particles (UFP), $PM_{2.5}$, O_3 and NO_2. Arter et al. showed that nearly 1200 (645 – 1800) premature deaths (in the US, which was the domain of study) are attributable to aviation LTO emissions with 92% of these due to NO_2 (Arter et al. 2022). Exposures to NO_2 also cause 170,000 (4,400 – 340,000) excess asthma exacerbations in the U.S. Further, they show that implementing a 50% blend of sustainable alternate fuels (SAFs) result in a 18% reduction in $PM_{2.5}$ attributable premature mortalities, but the LTO-attributable NO_2 to be unaffected by the implementation of SAFs. Thus, while transitioning to SAFs may lead to reductions in CO_2 (not discussed in this section) and direct $PM_{2.5}$ related health impacts, additional NO_x reductions are needed to mitigate the air quality-related health impacts from LTO emissions. Given the increasing role of NO_2 from aircraft emissions on public health, it is also important to have better characterization of aircraft plumes around airports to study local-scale air quality, where NO_2 may be of concern. For example, the United States regulatory model has shown to have several deficiencies in modelling the hot buoyant plume from aircraft exhaust (Arunachalam et al. 2019) and recent efforts to characterize plume rise due to aircraft emissions in local-scale dispersion models (Pandey, Venkatram, and Arunachalam 2023) need to be considered for local-scale air quality studies.

Ultrafine particle concentrations (UFP, $D_p < 100$ nm) are also of interest when considering local scale air quality impacts due to aircraft emissions. Several airport studies have emerged globally (airports including Los Angeles, Boston Logan, Seattle Tacoma, London Heathrow, Schiphol, Frankfurt, Copenhagen, etc.) showing elevated levels of UFP exposures at downwind distances from the airport, and increased attention needs to be given to the formation of UFP from aircraft during LTO operations. Mueller et al. (2022) observed mean reductions of 48% in particle number concentrations (PNC) near the Boston Logan airport, due to 74% lower flight activity and 39% lower traffic volume due to the 2020 – 2021 COVID-19 related pandemic (Mueller et al. 2022). Post-pandemic, they saw a 23% lower level of PNC at a site downwind from Logan attributable to a 44% lower flight activity from pre-pandemic levels.

3. MITIGATION OF AVIATION ENVIRONMENTAL IMPACTS

Estimates of the climate impact from aviation are based on four aspects affecting emissions from an aircraft, namely the aircraft and engine technology, the energy carrier or fuel used, the concept of operations of the flights (i.e., the way the routing is performed, the trajectory flown etc), and finally the response of the atmosphere to those emissions. These factors are coupled, and a new technology might affect all four emissions aspects. For example, the analysed multi-fuel blended-wing body (Gangoli Rao, Yin, and P. van Buijtenen 2014) that uses liquid hydrogen and SAFs as fuels in two subsequent combustion chambers has a higher overall efficiency, a low NO_x emissions index, and particulate emissions, but a higher optimal cruise altitude. Especially the combination of hydrogen as a fuel and a higher flight altitude significantly increases the climate impact from water vapor emissions into the stratosphere (Grewe et al. 2017; Pletzer et al. 2022). Hence any mitigation of the climate impact of aviation that targets one of the four components, might implicitly affect all others. In addition, assessing mitigation options also implies a careful analysis of the basic scenario assumptions, e.g., fleet development and other factors, and a climate metric that is well adapted to the addressed objective (Grewe and Dahlmann 2015). This implies that the current ratio of non-CO_2 climate effects to the CO_2 climate effect (estimated to be around 2) for the ERF in 2018 from all emissions since 1940 (Lee et al. 2021) might significantly differ for individual sectors, such as short-, medium- and long-range aircraft (Grewe et al. 2017) leading to different weighs between non-CO_2 and CO_2 in the mitigation of their climate impacts.

The resilient growth of aviation sector is an ongoing concern for the climate. The recent pandemic provided an opportunity for discussion on the environmental impacts of air traffic, its various pathways of growth, and the efficiencies of climate policies (Gössling and Humpe 2020). The reduction of aviation and other emissions due to COVID-19 lockdowns led to discernible changes in atmospheric composition, for instance in tropospheric nitrogen oxides, ozone, methane and OH (Weber et al., 2020; Steinbrecht et al., 2021; Mertens et al., 2021; Peng et al., 2022; Stevenson et al., 2022). Despite the temporary decrease, global aviation traffic and emissions recovered after the COVID-19 pandemic and meet the projected growth rates to 2050. The reduction of aviation climate impact due to COVID-19 is small, mostly because of the cumulative nature of the CO_2-induced warming and is estimated to only delay aviation contribution to warming (Grewe et al. 2021; Klöwer et al. 2021).

New technologies and fuels for NO_x and nvPM reduction

Technology solutions to reduce the emissions of NO_x and nvPM per unit fuel burn (e.g., emissions indices) are predominantly at the engine and combustor level. Aircraft system level efficiency improvements will reduce fuel burn which in turn reduces both the CO_2 impacts (not the focus of this report, please refer to other prior CAEP work such as (Cumpsty et al. 2019)) as well as the total emissions of NO_x, SO_x, nvPM etc. Recent research projects to mitigate aviation environmental impacts have explored concepts to reduce NO_x emissions from the gas turbine through modifications to the thermodynamic cycle or through the unconventional power trains. Advanced Rich Quench Lean (RQL) and Lean Burn (LB) are both active areas of progress and research. For advanced RQL there are well understood trade-offs between NO_x and nvPM emission reductions. LB combustion offers the potential for controlling both NO_x and nvPM emissions at full power and cruise conditions and there are significant operability and scalability issues associated with LB combustion developments. To continue reductions in fuel burn and emissions (NO_x and nvPM), whilst retaining operability criteria of the combustion technology, these technologies have been improving with time (CAEP/13-WG3/4-WP/04, 2023).

Other conceptual studies suggest the use of post-combustion emissions control (Prashanth et al. 2021) as a means to minimize or eliminate aviation NO_x emissions. A trend towards power dense engine cores with reduced core size (characterized by the corrected mass flow at compressor exit) and architectures that decouple thrust production from shaft power production (e.g., a turbo-electric system) may present opportunities to treat the core exhaust gases. Such technology in future architectures, coupled with use of SAFs may further open the design space for engine designers to optimize the thermodynamic cycle and combustion to minimize fuel burn and other pollutants such as nvPM. The feasibility of such propulsion-airframe integrated architectures needs to be further researched.

Yin et al. (2020) investigated the impacts of a regional/narrow-body hybrid electric aircraft (HEA) on contrail formation and potential contrail coverage (Yin, Grewe, and Gierens 2020). In general, they found that HEA have smaller areas for contrail formation when the degree of electrification used in operation increases. Their results show that a small degree of hybridization (below 30%) shows only marginal changes in potential contrail coverage. In contrast, a maximum decrease of 40% in potential contrail coverage was found locally for a 90% electrification, indicating that a targeted used of the electrification during cruise, i.e., in ice supersaturated regions, might be relevant to avoid the formation of contrails by hybrid electric aircraft.

Sustainable alternate fuels and energy carriers

The reduction of fossil-based CO_2 emissions is the main lever (and policy requirement) associated with climate protection. An increase in uptake of SAFs (in order to reduce CO_2 emissions) is likely to also reduce SO_2 and soot emissions as a co-benefit. If liquid hydrogen is considered, the H_2 combustion will lead to no soot or SO_x emissions, however there will be an increase in direct water vapour emissions. As a result, the contrails formed will have different characteristics in terms of density, lifetime, and radiative effects (Bier et al. 2024; Lee et al. 2023; Märkl et al. 2024; Ponater et al. 2006) (see the ISG Contrail Science Workshop report for further details). Emissions of NO_x per unit of fuel burn are not directly impacted by the choice of hydrocarbon based SAF, since they are a function of high-temperature combustion and result from the combining of atmospheric nitrogen and oxygen (fuel bound nitrogen is a negligible contribution for most aviation fuels). The magnitude of the non-CO_2 co-benefits (both with respect to climate and global air quality) resulting from utilizing SAF has currently large uncertainties and requires more work (there is relatively higher confidence regarding the local air quality benefits from reducing soot emissions, for example). In light of the need to substantially reduce the climate impacts of aviation and considering the current TRL levels of advanced technologies and the need of green electricity to produce the required volume of synthetic jet fuel, it has been suggested and demonstrated that climate-neutral aviation can happen through air traffic reduction (Gössling and Humpe 2020; Klöwer et al. 2021; Sacchi et al. 2023).

Recent work by Adler et al. (2023) analyses the potential for hydrogen fuelled aircraft (Adler and Martins 2023). From a climate perspective, hydrogen aircraft can have a lower impact than conventional aircraft, provided the hydrogen is produced using renewable energy sources such as wind, solar, or nuclear power. These aircraft produce no in-flight CO_2 (lifecycle emissions of producing the hydrogen still need to be accounted for) and while the adiabatic flame temperature of hydrogen combustion is higher, specifically designed combustors may result in a reduction in NO_x emissions via improved mixing and leaner combustion (simply switching the fuel without modifying the combustion systems could result in an increase in NO_x production). The impact of hydrogen fuelled aircraft on persistent contrails and contrail cirrus is uncertain. However, rerouting flights to avoid regions where warming persistent contrails are likely to form may mitigate this issue (refer to the ISG Contrail Science workshop Report for further details). In the case of hydrogen, it should also be noticed that reducing the leakage rate during production, transport and use, and increasing the renewable hydrogen production pathway appear as the key leverages towards a maximum mitigation of the climate impact (Hauglustaine et al., 2022). It should also be kept in mind that the hydrogen combustion and novel engine cycle research is currently at low TRL.

Impact of trajectory changes

Matthes et al. (2021) and Terrenoire et al. (2022) investigated the climate impact reductions potential by flying generally lower or higher by 1000 ft by considering CO_2, NO_x, contrails and aerosol-cloud effects. The results agree with earlier studies (Frömming et al. 2012), showing a reduction of non-CO_2 effects for lower altitudes, while CO_2 emissions increase.

Linke et al. (2017) studied the climate impact of intermediate-stop operations (ISO) for a global fleet. They concluded that intermediate-stop operations could achieve approximately a 5% fuel reduction and decreased contrail impact due to higher cruise altitudes. However, the higher altitudes of the first flight leg due to lower take-off weights resulted in increased NO_x and H_2O impacts, which offset the benefits from fuel savings and reduced contrails. Zengerlin et al. (2023) revised this study and found that by selecting the most fuel-efficient trajectories that do not increase climate impact, fuel consumption can be reduced by 1.3% and the overall climate impact (measured by ATR100) by 2.1% compared to conventional operations (Zengerling et al. 2023).

Dahlmann et al. examined the potential for reducing climate impact by flying two aircraft in aerodynamic formation (Dahlmann et al. 2020). This study is based on prior detailed fleet analysis (Marks et al. 2021) and Large Eddy Simulations (LES) of contrail interactions by Unterstrasser (2020). By analyzing the top 50 city pair connections while maintaining the same flight altitude and speed as a reference, they found a total climate impact reduction of 22% (**Figure 5**). Although the flight distance increases with aerodynamic formation, wake energy retrieval reduces fuel consumption by around 5%, which results in a 1% reduction in climate impact. Additionally, the reduced thrust settings due to wake energy retrieval lower NO_x emission indices, leading to a 10% reduction in NO_x emissions. The most significant reduction in climate impact comes from contrails, as the two contrails formed during formation flights compete for water vapor, inhibiting their growth. Consequently, contrail ice mass and total extinction are significantly smaller than those from two separate aircraft and contrails (Unterstrasser 2020).

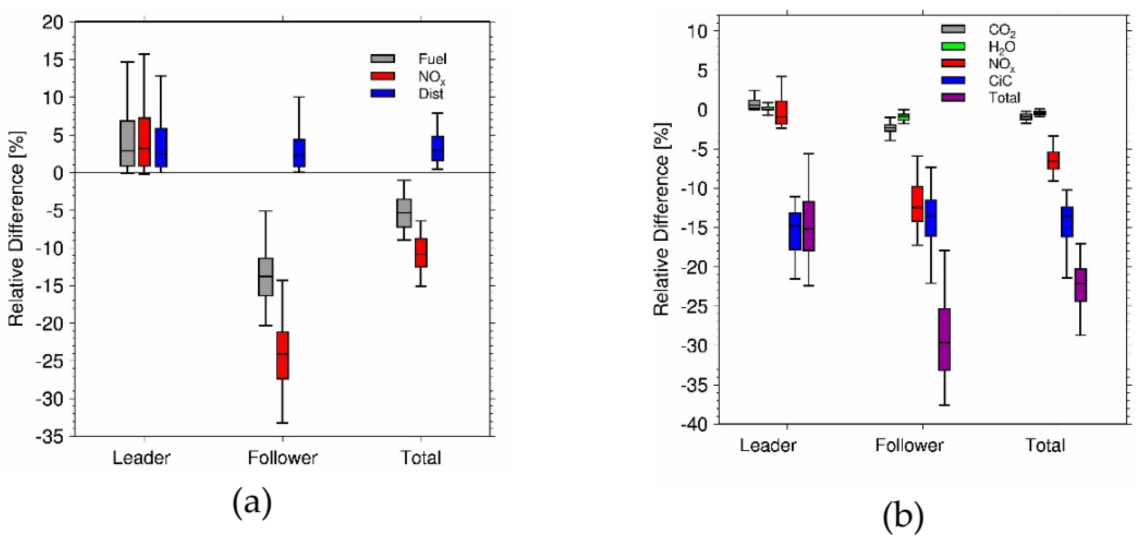

Figure 5. (a) Relative change in fuel consumption, NO_x emissions and flown distances for leader, follower and the total formation for the Top50 scenario compared to the reference case where both aircraft fly not in formation. (b) Change in total climate impact and climate impact of the different species relative to the change in total climate impact. The bars indicate the 25% and 50% percentile and the whiskers indicate the 95% confidence interval of the different formations in one data set (Dahlmann et al. 2020).

Using daily weather data in trajectory optimization can reduce climate impact by avoiding climate-sensitive regions. These regions were identified using a Lagrangian simulation approach, which tracks individual air parcels and quantifies the climate impact of aviation emissions for CO_2, H_2O, NO_x, and contrails (Grewe et al. 2014). The results show a patchy pattern for contrails (Frömming et al. 2021) and a clear relationship between NO_x and H_2O climate impacts and meteorological data such as geopotential, temperature, and tropopause altitudes (Frömming et al. 2021; Maruhashi et al. 2022). Rosanka et al. (2020) demonstrated that the climate impact of local NO_x emissions leads to a large and early ozone increase when transported to lower latitudes, whereas the ozone gain is smaller and later if the air parcel remains at mid-latitudes. This data was used to optimize North Atlantic flights, resulting in a climate impact reduction of around 15% at a cost of less than 1% of cash operating costs, which could be mitigated by including non-CO_2 effects in a market-based measure (Grewe et al., 2017).

The clear relation of the climate sensitive regions with meteorology lead to the development of the algorithmic climate change functions (aCCFs) (Dietmüller et al. 2023; van Manen and Grewe 2019; Matthes et al. 2021; Yin et al. 2023)that enable the inclusion into weather forecast models and thereby enables the information flow of climate sensitive regions to air traffic service providers. Matthes et al. (2017) provided a road map that indicates the steps required before those approaches can be used operationally. It also includes a validation or verification approach. First steps were undertaken in this respect by Sausen et al. (2023) who provided a statistical analysis for an avoidance of contrail experiment with in the Maastricht Upper Area Control (MUAC) airspace, and by Rao et al. (2022) and Yin et al. (2023) who provided a verification of NO_x-ozone aCCFs within a modelling framework. However, all such optimization efforts rely on meteorological data being proven to be sufficiently accurate.

Reducing impacts on air quality

The primary means of reducing the impacts of aviation emissions on boundary layer air quality would be through reduction in NO_x and particle emissions, the former because of its importance in ozone production and the latter because of its direct effects on human and ecosystem health. NO_x emissions are a result of high temperature combustion in air (where atmospheric nitrogen and oxygen react to form NO_x) and is largely dependent on engine design choices (e.g., high cycle pressure ratio for efficiency). Various analyses (Lee et al. 2023) indicate that the choice of fuels by the chemical formulation of aviation fuel to reduce aromatics could significantly reduce particle emissions. In particular, increased uptake of SAFs (and an associated decrease in fossil CO_2 emissions and potential decrease in soot emissions) may allow engine designers to focus design efforts on reducing NO_x emissions (Lee et al. 2023). The possible role of venting of engine oil for its contribution to volatile particle emissions, depending on the design of the engine and the engine venting mechanism, also needs to be better understood.

4. INTERDEPENDENCIES AND TRADE-OFFS IN MITIGATING AIR QUALITY AND CLIMATE IMPACTS

As aircraft technology improves, there are strong incentives to decrease emissions and other environmental impacts, and these improvements are often used to mitigate air quality and climate impacts. However, trade-offs occur when multiple environmentally harmful emission components respond in opposite directions to an engine/aircraft design change. For instance, if fuel burn were to be optimized with no constraints, the NO_x emissions would increase significantly due to higher combustor temperatures and pressures. Thus, there are trade-offs between these competing components when revising an engine/aircraft design. The impact of such a trade depends on both the technological trade (that is, the magnitude of each emissions change) and how the environmental impacts from those emissions changes are valued.

NO_x regulations have been in place for decades and NO_x emissions continue to be a major engine design parameter. Fuel burn has always been a key design criterion for aircraft and has recently been further emphasized with a CO_2 regulatory requirement. For these reasons, most work to date to understand air quality/climate trade-offs has been done for NO_x/CO_2. There are also trade-offs between non-volatile Particulate Matter (nvPM) emissions and NO_x emissions. Compared to NO_x/CO_2 trade-offs, little work is available for nvPM/NO_x, due to the complexities of the NO_x and nvPM dependences on combustion processes. As a result, nvPM/NO_x trade-off evaluations performed so far have not been quantitative nor detailed.

NO_x/CO_2 trades

When analysing the trade-off between NO_x and CO_2 emissions, the largest factors in evaluating the environmental impacts are the effects of CO_2 on climate and of NO_x on air quality. For the complete analysis, additional terms are included (such as NO_x impacts on climate), but those first two terms are the dominant ones. Considering climate impacts alone, studies by Freeman et al. (2018) and Skowron et al. (2021) have found that reductions in aviation NO_x emissions do not provide clear climate benefits if these reductions are achieved using design changes that increase CO_2 emissions. To compare air quality and climate impacts on a common basis, Grobler et al. (2019) monetized climate damages and air quality health impacts from aviation emissions. They found environmental costs of $45 per tonne CO_2 (2015 USD; 90% CI: 7 – 120) and $22,000 per tonne NO_x (90% CI: 2,500 – 71,000). Using updated meta-studies on the social cost of carbon (Howard and Sterner 2017; Rennert et al. 2022) and the health impacts of ozone and $PM_{2.5}$ exposure (Turner et al. 2016; Burnett et al. 2018; Quadros et al. 2020), the monetized damages increase to $113 – 168 per tonne CO_2 and $48,000 per tonne NO_x. In addition to relatively large uncertainties, monetized damages also vary depending on policy preferences for weighing impacts in the future, expressed in terms of the discount rate (DR). Air quality health impacts, which are relatively near-term, are nearly independent of DR, while impacts from long-lived climate forcers like CO_2 increase from $45/tonne to $95/tonne when considering a 2% DR instead of a 3% DR (Grobler et al. 2019) (**Fig. 6**).

Assuming the use of fossil-derived jet fuel with CORSIA-default lifecycle emissions, the monetized damages noted above can be used to estimate the amount of NO_x emissions that have the same monetized impact as the CO_2 emissions from 1 kg of fuel burn. Using the original damages from Grobler et al. (2019) this is 7.8 g NO_x/kg fuel, or 8.9 – 13.3 g NO_x/kg fuel using the updated impact estimates. For an engine with the global-average NO_x Emission Index (EI) of 15 g/kg (Skowron et al. 2021), these ratios suggest that a design change that reduces absolute NO_x emissions by 1% while increasing fuel burn by less than 1.1 – 1.9% would be net environmentally beneficial. The use of increasing quantities of SAFs with lower lifecycle CO_2 emissions would tend to suggest that even larger increases in fuel burn could be environmentally justified in favour of NO_x reductions. Miller et al. (2022) suggest the use of a “social cost of engine operation” which includes marginal fuel production costs as well air quality and climate costs, an approach which then accounts for the additional costs and production limitations of SAFs in comparison to fossil jet fuel.

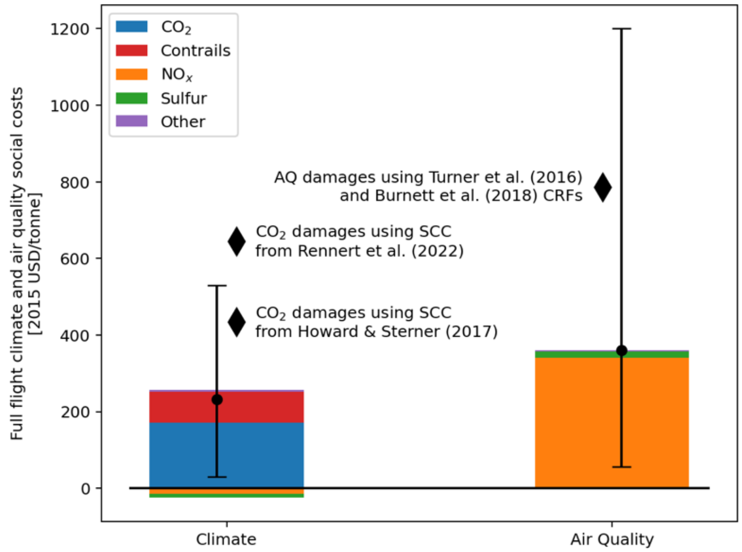

Figure 6. Full flight climate and social costs (2015 USD/tonne of fuel) due to climate impacts and air quality impacts, showing contributions from all identified emissions contributions: CO_2, contrails, NO_x, sulfur, and any other contributions. Adapted from (Grobler et al. 2019).

Different mitigation options have distinct effects on fuel burn/CO_2 and NO_x emissions. The Independent Experts Integrated Review (IEIR) Panel (Cumpsty et al. 2019) stated that trade-offs associated with minimizing NO_x emissions through combustor technology, at a fixed Overall Pressure Ratio (OPR) and T_{40}, are assumed to be less than a 0.5% increase in fuel burn/CO_2 emissions. The ICAO Engine Emissions Data Bank (EEDB) shows that NO_x EIs for engines with similar OPR have decreased by 40 – 60% over the past three decades, highlighting the advances made in combustor technology. However, further improvements via this route are likely to be more difficult than those attained already. Several studies in the literature have modelled the trade-off between NO_x and CO_2 with changes in OPR, finding fuel burn increases of 0.04% to 0.31% per percentage point reduction in NO_x, with the trade-off increasing as OPR decreases from its fuel burn optimum (Guynn et al. 2009; Thoma, Grönstedt, and Zhao 2020; Dinc 2021). Other engine technology improvements, such as increases in compressor efficiency, can reduce both the NO_x Emissions Index (EI) and CO_2, compounding the reduction in total NO_x (Dinc 2021) while technologies that reduce weight or improve aerodynamics will provide equal reductions in NO_x and CO_2.

By making the NO_x limit a function of OPR, the current CAEP/8 LTO NO_x standard allows engine designers to select OPR to meet design goals of their choice, with little need to consider the resulting NO_x emissions. Guynn et al. (2009) estimated that an increase in OPR from 26.7 to 34.6 reduced block fuel burn by 6% and increased total NO_x by 27%, while the CAEP/8 limit increases by 36% over this OPR range for engines with rated thrust greater than 89 kN. The higher OPR engine would have an increased margin to the CAEP/8 limit despite having 13 – 17% higher environmental impacts based on the valuations described above. Miller et al. (2022) derived formulations of the NO_x limit as a function of OPR that would make social costs independent of OPR, and also noted the alternative option of defining a NO_x standard using fuel consumption as a parameter directly instead of OPR as a means of minimizing the variation in social cost at different OPR.

nvPM/NO_x trades

Both NO_x and nvPM have air quality impacts, though these impacts occur at different scales: nvPM has local impacts, while NO_x has local to hemispheric impacts. Both have climate impacts: NO_x has multiple climate impact pathways (see Section 1) while nvPM emissions' largest global impacts are estimated to be through the contrails associated with nvPM emissions. No general quantitative trade-offs between nvPM and NO_x can be prescribed since the relative emissions amounts are highly technology dependent. That is to say, the nvPM/NO_x trade-off is different for Rich-Quick Quench Lean (RQL) combustors vs advanced RQL vs staged lean burn engine designs, so simple expressions for nvPM/NO_x trade-offs cannot be readily calculated since they are very sensitive to the geometric and flow field details of the combustor design in question (Cumpsty et al. 2019).

Relationship to aviation sector trends and future technologies

Industry and the scientific community have been investing substantial effort to be able to promote the aviation system to a better level of performance as well as minimizing negative impacts on the environment. Some of the main technology advances related to this effort include sustainable alternative fuels, new propulsion systems (electric, hydrogen, hybrid), unconventional airframe design, each of which is expected to have various contribution to overreach the goals. For instance, the IATA (International Air Transport Association) projects SAFs contribution in CO_2 reduction to reach net-zero in 2050 could be 65% IATA (2021). In addition, there has been significant momentum in the development of aircraft with electrified propulsion units, along with electrified Vertical Take-off and Landing (eVTOL) technologies. Hydrogen powered engines / fuel cells have also been receiving great interest. Furthermore, these strategies appear to accelerate the studies on unconventional airframes, which have been long been a subject of research interest.

On the other hand, despite the improvement in performance as well as emission impact with each generation of aircraft, forcing an aircraft to execute an indeterminate holding in the terminal manoeuvre area or vertical inefficiencies (e.g., stair step descent) due mainly to congestion, or other factors diverting the aircraft from efficient routes (e.g. restricted areas) and creating horizontal inefficiencies, could negate a considerable portion of the benefits one would expect to gain. Therefore, considering also the growth in aviation (despite the fluctuations), without reaching a highly efficient air traffic management system, (while the safety has the overriding priority), perhaps it will be challenging to achieve expected gains with all those advancements in aircraft technologies.

CONCLUSION

A comprehensive approach is needed to address the total climate impact of aviation, but this poses several challenges as it must address both short-lived climate forcers and long-lived greenhouse gases: some of the impacts are cooling or warming effects, while others have both warming and cooling components acting at various time scales. Despite the growth in knowledge over the last few decades, there is still a lack of confidence in recommending definitive strategic action on aviation's non-CO_2 emissions for climate change mitigation. This is largely because the climate impact of aviation's non-CO_2 emissions remains highly uncertain. This is in contrast to the impact of CO_2, which is well understood. Recent studies suggest that the sign of the net NO_x radiative forcing could even change from positive to negative if indirect aerosol effects or changing future atmospheric background conditions are considered. The net direct aviation-aerosol radiative forcing is also estimated to be negative because of the dominant cooling effect of sulphates and, to a lesser extent, nitrates over the warming effect of soot. However, aerosols can also interact with low- and high-level clouds and these indirect climate effects remain highly uncertain in both sign and magnitude. The specific aspect of climate change (short-term or long-term, etc.) and therefore the choice of an appropriate climate metric used to quantify the climate impact of aviation non-CO_2 emissions, and even the attribution method used to determine their relative contribution to the overall climate impact of aviation, also affect the estimate of the climate impact of aviation non-CO_2 emissions and are the subject of active scientific research.

Aviation emissions contribute to air quality degradation by increasing near-surface concentrations of harmful pollutants, both through direct emissions of these pollutants (e.g. ultrafine particulate matter) and through the emission of precursor pollutants (e.g. ozone formed as a result of aircraft NO_x emissions). The impact of aviation emissions on air quality is now understood to include both global effects resulting from emissions during flight and local to regional effects resulting from emissions in the vicinity of airports. There is growing evidence that the increase in aviation air pollution at the hemispheric scale is largely associated with cruise emissions and further redistribution to the surface through atmospheric transport. The exception is exposure to nvPM, which is mostly from local sources, but accounts for less than 1% of population exposure to PM2.5 from aviation and is irrelevant to ozone impacts. Aircraft emissions during the LTO phase have also been shown to cause health effects through exposure to NO_2 concentrations. Given the increasing importance of NO_2 from aircraft emissions to public health, it is important to have a better characterisation of aircraft plumes around airports to better investigate local air quality where NO_2 may be of concern.

There are a significant number of technologies and aircraft operations, at varying levels of maturity, that can be used to achieve reductions in both fuel consumption and environmentally harmful emissions. Where these technologies and design choices involve trade-offs between multiple concerns, monetisation of environmental impacts maybe be one solution to provide a means of comparing technologies and identifying environmentally beneficial solutions. However, it should be kept in mind that the monetisation metric relies on strong assumptions related to cost damage estimates or to geographical inhomogeneities not easy to account for to derive a robust global metric. Such environmental analyses can also be used to evaluate trade-offs that are implicit in emission standards, or to inform how they could be explicitly accounted for. In the former case, it may be necessary to update the form of a standard as different technologies become available. In the latter case, the quantification of trade-offs should be periodically reassessed as scientific understanding of the climate and air quality impacts of aviation improves, and monetisation of these impacts is refined.

LIST OF ABBREVIATIONS

aCFF	Algorithmic Climate Change Functions
AGWP	Absolute Global Warming Potential ($J.m^{-2}$)
ATR	Average Temperature Response (°C)
CAEP	Committee for Aviation Environmental Protection
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DR	Discount Rate
EEDB	Engine Emissions Databank
EI	Emission Index ($kg.kg\text{-}fuel^{-1}$)
ERF	Effective Radiative Forcing ($W.m^{-2}$)
GHG	Greenhouse Gas
GTP	Global Temperature–change Potential
GWP	Global Warming Potential
HEA	Hybrid Electric Aircraft
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEIR	Independent Experts Integrated Review
IPCC	Intergovernmental Panel on Climate Change
ISG	Impacts and Science Group
ISO	Intermediate-stop-operations
LB	Lean Burn
LES	Large Eddy Simulations
LTO	Landing and Take-off
MUAC	Maastricht Upper Area Control
NO_x	Oxides of Nitrogen ($NO + NO_2$)
OH	Hydroxyl Radical
OPR	Overall Pressure Ratio
PNC	Particle Number Concentrations
RF	Radiative Forcing ($W.m^{-2}$)
RQL	Rich Quench Lean
SAF	Sustainable Aviation Fuel
SCC	Social Cost of Carbon
SO_x	Oxides of Sulphur
SWV	Stratospheric Water Vapor
TRL	Technology Readiness Level
UFP	Ultrafine Particle concentration

REFERENCES

Adler, Eytan J., and Joaquim R. R. A. Martins. 2023. "Hydrogen-Powered Aircraft: Fundamental Concepts, Key Technologies, and Environmental Impacts." *Progress in Aerospace Sciences* 141:100922. doi: 10.1016/j.paerosci.2023.100922.

Allen, Myles R., Glen P. Peters, Keith P. Shine, Christian Azar, Paul Balcombe, Olivier Boucher, Michelle Cain, Philippe Ciais, William Collins, Piers M. Forster, Dave J. Frame, Pierre Friedlingstein, Claire Fyson, Thomas Gasser, Bill Hare, Stuart Jenkins, Steven P. Hamburg, Daniel J. A. Johansson, John Lynch, Adrian Macey, Johannes Morfeldt, Alexander Nauels, Ilissa Ocko, Michael Oppenheimer, Stephen W. Pacala, Raymond Pierrehumbert, Joeri Rogelj, Michiel Schaeffer, Carl F. Schleussner, Drew Shindell, Ragnhild B. Skeie, Stephen M. Smith, and Katsumasa Tanaka. 2022. "Indicate Separate Contributions of Long-Lived and Short-Lived Greenhouse Gases in Emission Targets." *Npj Climate and Atmospheric Science* 5(1):1–4. doi: 10.1038/s41612-021-00226-2.

Arter, Calvin A., Jonathan J. Buonocore, Chowdhury Moniruzzaman, Dongmei Yang, Jiaoyan Huang, and Saravanan Arunachalam. 2022. "Air Quality and Health-Related Impacts of Traditional and Alternate Jet Fuels from Airport Aircraft Operations in the U.S." *Environment International* 158:106958. doi: 10.1016/j.envint.2021.106958.

Arunachalam, Saravanan, Brian Naess, Catherine Seppanen, Alejandro Valencia, Jo Ellen Brandmeyer, Akula Venkatram, Jeffrey Weil, Vlad Isakov, and Timothy Barzyk. 2019. "A New Bottom-up Emissions Estimation Approach for Aircraft Sources in Support of Air Quality Modelling for Community-Scale Assessments around Airports." *International Journal of Environment and Pollution* 65(1/2/3):43. doi: 10.1504/IJEP.2019.101832.

Barrett, Steven R. H., Rex E. Britter, and Ian A. Waitz. 2010. "Global Mortality Attributable to Aircraft Cruise Emissions." *Environmental Science & Technology* 44(19):7736–42. doi: 10.1021/es101325r.

Bier, Andreas, Simon Unterstrasser, Josef Zink, Dennis Hillenbrand, Tina Jurkat-Witschas, and Annemarie Lottermoser. 2024. "Contrail Formation on Ambient Aerosol Particles for Aircraft with Hydrogen Combustion: A Box Model Trajectory Study." *Atmospheric Chemistry and Physics* 24(4):2319–44. doi: 10.5194/acp-24-2319-2024.

Boucher, Olivier, Audran Borella, Thomas Gasser, and Didier Hauglustaine. 2021. "On the Contribution of Global Aviation to the CO2 Radiative Forcing of Climate." *Atmospheric Environment* 267:118762. doi: 10.1016/j.atmosenv.2021.118762.

Brasseur, G. P., R. A. Cox, D. Hauglustaine, I. Isaksen, J. Lelieveld, D. H. Lister, R. Sausen, U. Schumann, A. Wahner, and P. Wiesen. 1998. "European Scientific Assessment of the Atmospheric Effects of Aircraft Emissions." *Atmospheric Environment* 32(13):2329–2418. doi: 10.1016/S1352-2310(97)00486-X.

Brasseur, Guy P., Mohan Gupta, Bruce E. Anderson, Sathya Balasubramanian, Steven Barrett, David Duda, Gregg Fleming, Piers M. Forster, Jan Fuglestvedt, Andrew Gettelman, Rangasayi N. Halthore, S. Daniel Jacob, Mark Z. Jacobson, Arezoo Khodayari, Kuo-Nan Liou, Marianne T. Lund, Richard C.

Miake-Lye, Patrick Minnis, Seth Olsen, Joyce E. Penner, Ronald Prinn, Ulrich Schumann, Henry B. Selkirk, Andrei Sokolov, Nadine Unger, Philip Wolfe, Hsi-Wu Wong, Donald W. Wuebbles, Bingqi Yi, Ping Yang, and Cheng Zhou. 2016. "Impact of Aviation on Climate: FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II." *Bulletin of the American Meteorological Society* 97(4):561–83. doi: 10.1175/BAMS-D-13-00089.1.

Brasseur, Guy P., Jean-François Müller, and Claire Granier. 1996. "Atmospheric Impact of NOx Emissions by Subsonic Aircraft: A Three-Dimensional Model Study." *Journal of Geophysical Research: Atmospheres* 101(D1):1423–28. doi: 10.1029/95JD02363.

Brazzola, Nicoletta, Anthony Patt, and Jan Wohland. 2022. "Definitions and Implications of Climate-Neutral Aviation." *Nature Climate Change* 12(8):761–67. doi: 10.1038/s41558-022-01404-7.

Burnett, Richard, Hong Chen, Mieczysław Szyszkowicz, Neal Fann, Bryan Hubbell, C. Arden Pope, Joshua S. Apte, Michael Brauer, Aaron Cohen, Scott Weichenthal, Jay Coggins, Qian Di, Bert Brunekreef, Joseph Frostad, Stephen S. Lim, Haidong Kan, Katherine D. Walker, George D. Thurston, Richard B. Hayes, Chris C. Lim, Michelle C. Turner, Michael Jerrett, Daniel Krewski, Susan M. Gapstur, W. Ryan Diver, Bart Ostro, Debbie Goldberg, Daniel L. Crouse, Randall V. Martin, Paul Peters, Lauren Pinault, Michael Tjepkema, Aaron van Donkelaar, Paul J. Villeneuve, Anthony B. Miller, Peng Yin, Maigeng Zhou, Lijun Wang, Nicole A. H. Janssen, Marten Marra, Richard W. Atkinson, Hilda Tsang, Thuan Quoc Thach, John B. Cannon, Ryan T. Allen, Jaime E. Hart, Francine Laden, Giulia Cesaroni, Francesco Forastiere, Gudrun Weinmayr, Andrea Jaensch, Gabriele Nagel, Hans Concin, and Joseph V. Spadaro. 2018. "Global Estimates of Mortality Associated with Long-Term Exposure to Outdoor Fine Particulate Matter." *Proceedings of the National Academy of Sciences* 115(38):9592–97. doi: 10.1073/pnas.1803222115.

Burnett, Richard T., C. Arden Pope, Majid Ezzati, Casey Olives, Stephen S. Lim, Sumi Mehta, Hwashin H. Shin, Gitanjali Singh, Bryan Hubbell, Michael Brauer, H. Ross Anderson, Kirk R. Smith, John R. Balmes, Nigel G. Bruce, Haidong Kan, Francine Laden, Annette Prüss-Ustün, Michelle C. Turner, Susan M. Gapstur, W. Ryan Diver, and Aaron Cohen. 2014. "An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure." *Environmental Health Perspectives* 122(4):397–403. doi: 10.1289/ehp.1307049.

Cameron, M. A., M. Z. Jacobson, S. R. H. Barrett, H. Bian, C. C. Chen, S. D. Eastham, A. Gettelman, A. Khodayari, Q. Liang, H. B. Selkirk, N. Unger, D. J. Wuebbles, and X. Yue. 2017. "An Intercomparative Study of the Effects of Aircraft Emissions on Surface Air Quality." *Journal of Geophysical Research: Atmospheres* 122(15):8325–44. doi: 10.1002/2016JD025594.

Cames, Martin, Jakob Graichen, Anne Siemons, and Vanessa Cook. 2015. *Emission Reduction Targets for International Aviation and Shipping*. IP/A/ENVI/2015-11. Brussels: European Parliment.

Collins, William J., David J. Frame, Jan S. Fuglestvedt, and Keith P. Shine. 2020. "Stable Climate Metrics for Emissions of Short and Long-Lived Species—Combining Steps and Pulses." *Environmental Research Letters* 15(2):024018. doi: 10.1088/1748-9326/ab6039.

Cumpsty, Nick, Dimitri Mavris, Juan Alonso, Fernando Catalano, Chris Eyers, Marius Goutines, Tomas Grönstedt, Dr Jim Hileman, Alain Joselzon, Iurii Khaletskii, Frank Ogilvie, Malcolm Ralph, Dr Jayant

Sabnis, Dr Richard Wahls, and David Zingg. 2019. *Independent Expert Integrated Technology Goals Assessment and Review for Engines and Aircraft*. Doc 10127. Montreal: ICAO.

Dahlmann, Katrin, Sigrun Matthes, Hiroshi Yamashita, Simon Unterstrasser, Volker Grewe, and Tobias Marks. 2020. "Assessing the Climate Impact of Formation Flights." *Aerospace* 7(12):172. doi: 10.3390/aerospace7120172.

Dasadhikari, Kingshuk, Sebastian D. Eastham, Florian Allroggen, Raymond L. Speth, and Steven R. H. Barrett. 2019. "Evolution of Sectoral Emissions and Contributions to Mortality from Particulate Matter Exposure in the Asia-Pacific Region between 2010 and 2015." *Atmospheric Environment* 216:116916. doi: 10.1016/j.atmosenv.2019.116916.

Dickson Neil, Lee, D.S. et al. "CAEP Impacts and Science Group (ISG)- Contrail Science Workshop Report". CAEP, ICAO, 2025, https://www.icao.int/sites/default/files/environmental-protection/Documents/ScientificUnderstanding/CAEP14-ISG-ContrailWorkshop.pdf

Dietmüller, Simone, Sigrun Matthes, Katrin Dahlmann, Hiroshi Yamashita, Abolfazl Simorgh, Manuel Soler, Florian Linke, Benjamin Lührs, Maximilian M. Meuser, Christian Weder, Volker Grewe, Feijia Yin, and Federica Castino. 2023. "A Python Library for Computing Individual and Merged Non-CO_2 Algorithmic Climate Change Functions: CLIMaCCF V1.0." *Geoscientific Model Development* 16(15):4405–25. doi: 10.5194/gmd-16-4405-2023.

Dinc, A. 2021. "The Effect of Flight and Design Parameters of a Turbofan Engine on Global Warming Potential." *IOP Conference Series: Materials Science and Engineering* 1051(1):012051. doi: 10.1088/1757-899X/1051/1/012051.

Dockery, Douglas W., C. Arden Pope, Xiping Xu, John D. Spengler, James H. Ware, Martha E. Fay, Benjamin G. Ferris, and Frank E. Speizer. 1993. "An Association between Air Pollution and Mortality in Six U.S. Cities." *New England Journal of Medicine* 329(24):1753–59. doi: 10.1056/NEJM199312093292401.

Dray, Lynnette, Andreas W. Schäfer, Carla Grobler, Christoph Falter, Florian Allroggen, Marc E. J. Stettler, and Steven R. H. Barrett. 2022. "Cost and Emissions Pathways towards Net-Zero Climate Impacts in Aviation." *Nature Climate Change* 12(10):956–62. doi: 10.1038/s41558-022-01485-4.

Eastham, Sebastian D., and Steven R. H. Barrett. 2016. "Aviation-Attributable Ozone as a Driver for Changes in Mortality Related to Air Quality and Skin Cancer." *Atmospheric Environment* 144:17–23. doi: 10.1016/j.atmosenv.2016.08.040.

Eastham, Sebastian D., Guillaume P. Chossière, Raymond L. Speth, Daniel J. Jacob, and Steven R. H. Barrett. 2024. "Global Impacts of Aviation on Air Quality Evaluated at High Resolution." *Atmospheric Chemistry and Physics* 24(4):2687–2703. doi: 10.5194/acp-24-2687-2024.

Eastham, Sebastian D., Thibaud Fritz, Inés Sanz-Morère, Prakash Prashanth, Florian Allroggen, Ronald G. Prinn, Raymond L. Speth, and Steven R. H. Barrett. 2022. "Impacts of a Near-Future Supersonic Aircraft Fleet on Atmospheric Composition and Climate." *Environmental Science: Atmospheres*. doi: 10.1039/D1EA00081K.

Forster, Peirs, and Trude Storelvmo. 2023. *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 1st ed. Cambridge University Press.

Freeman, Sarah, David S. Lee, Ling L. Lim, Agnieszka Skowron, and Ruben Rodriguez De León. 2018. "Trading off Aircraft Fuel Burn and NOx Emissions for Optimal Climate Policy." *Environmental Science & Technology* 52(5):2498–2505. doi: 10.1021/acs.est.7b05719.

Frömming, C., M. Ponater, K. Dahlmann, V. Grewe, D. S. Lee, and R. Sausen. 2012. "Aviation-Induced Radiative Forcing and Surface Temperature Change in Dependency of the Emission Altitude." *Journal of Geophysical Research: Atmospheres* 117(D19). doi: 10.1029/2012JD018204.

Frömming, Christine, Volker Grewe, Sabine Brinkop, Patrick Jöckel, Amund S. Haslerud, Simon Rosanka, Jesper van Manen, and Sigrun Matthes. 2021. "Influence of Weather Situation on Non-CO_2 Aviation Climate Effects: The REACT4C Climate Change Functions." *Atmospheric Chemistry and Physics* 21(11):9151–72. doi: 10.5194/acp-21-9151-2021.

Gangoli Rao, Arvind, Feijia Yin, and Jos P. van Buijtenen. 2014. "A Hybrid Engine Concept for Multi-Fuel Blended Wing Body" edited by R. Singh. *Aircraft Engineering and Aerospace Technology: An International Journal* 86(6):483–93. doi: 10.1108/AEAT-04-2014-0054.

Gao, Hang. 2013. "Aircraft Cruise Phase Altitude Optimization Considering Contrail Avoidance." Thesis, Massachusetts Institute of Technology.

Gierens, Klaus, Ling Lim, and Kostas Eleftheratos. 2008. "A Review of Various Strategies for Contrail Avoidance." *The Open Atmospheric Science Journal* 2(1):1–7. doi: 10.2174/1874282300802010001.

Gössling, Stefan, and Andreas Humpe. 2020. "The Global Scale, Distribution and Growth of Aviation: Implications for Climate Change." *Global Environmental Change* 65:102194. doi: 10.1016/j.gloenvcha.2020.102194.

Grewe, Volker, Lisa Bock, Ulrike Burkhardt, Katrin Dahlmann, Klaus Gierens, Ludwig Hüttenhofer, Simon Unterstrasser, Arvind Gangoli Rao, Abhishek Bhat, Feijia Yin, Thoralf G. Reichel, Oliver Paschereit, and Yeshayahou Levy. 2017. "Assessing the Climate Impact of the AHEAD Multi-Fuel Blended Wing Body." *Meteorologische Zeitschrift* 711–25. doi: 10.1127/metz/2016/0758.

Grewe, Volker, Thierry Champougny, Sigrun Matthes, Christine Frömming, Sabine Brinkop, Ole Amund Søvde, Emma A. Irvine, and Lucia Halscheidt. 2014. "Reduction of the Air Traffic's Contribution to Climate Change: A REACT4C Case Study." *Atmospheric Environment* 94:616–25. doi: 10.1016/j.atmosenv.2014.05.059.

Grewe, Volker, and Katrin Dahlmann. 2015. "How Ambiguous Are Climate Metrics? And Are We Prepared to Assess and Compare the Climate Impact of New Air Traffic Technologies?" *Atmospheric Environment* 106:373–74. doi: 10.1016/j.atmosenv.2015.02.039.

Grewe, Volker, Arvind Gangoli Rao, Tomas Grönstedt, Carlos Xisto, Florian Linke, Joris Melkert, Jan Middel, Barbara Ohlenforst, Simon Blakey, Simon Christie, Sigrun Matthes, and Katrin Dahlmann. 2021. "Evaluating the Climate Impact of Aviation Emission Scenarios towards the Paris Agreement

Including COVID-19 Effects." *Nature Communications* 12(1):3841. doi: 10.1038/s41467-021-24091-y.

Grobler, Carla, Philip J. Wolfe, Kingshuk Dasadhikari, Irene C. Dedoussi, Florian Allroggen, Raymond L. Speth, Sebastian D. Eastham, Akshat Agarwal, Mark D. Staples, Jayant Sabnis, and Steven R. H. Barrett. 2019. "Marginal Climate and Air Quality Costs of Aviation Emissions." *Environmental Research Letters* 14(11):114031. doi: 10.1088/1748-9326/ab4942.

Guynn, Mark D., Jeffrey J. Berton, Kenneth L. Fisher, William J. Haller, Michael Tong, and Douglas R. Thurman. 2009. *Engine Concept Study for an Advanced Single-Aisle Transport*. L–19712.

Hauglustaine, Didier A., and Brigitte Koffi. 2012. "Boundary Layer Ozone Pollution Caused by Future Aircraft Emissions." *Geophysical Research Letters* 39(13). doi: 10.1029/2012GL052008.

Hauglustaine, Didier, Fabien Paulot, William Collins, Richard Derwent, Maria Sand, and Olivier Boucher. 2022. "Climate Benefit of a Future Hydrogen Economy." *Communications Earth & Environment* 3(1):1–14. doi: 10.1038/s43247-022-00626-z.

Howard, Peter H., and Thomas Sterner. 2017. "Few and Not So Far Between: A Meta-Analysis of Climate Damage Estimates." *Environmental and Resource Economics* 68(1):197–225. doi: 10.1007/s10640-017-0166-z.

Huq, Nabila A., Glenn R. Hafenstine, Xiangchen Huo, Hannah Nguyen, Stephen M. Tifft, Davis R. Conklin, Daniela Stück, Jim Stunkel, Zhibin Yang, Joshua S. Heyne, Matthew R. Wiatrowski, Yimin Zhang, Ling Tao, Junqing Zhu, Charles S. McEnally, Earl D. Christensen, Cameron Hays, Kurt M. Van Allsburg, Kinga A. Unocic, Harry M. Meyer, Zia Abdullah, and Derek R. Vardon. 2021. "Toward Net-Zero Sustainable Aviation Fuel with Wet Waste–Derived Volatile Fatty Acids." *Proceedings of the National Academy of Sciences* 118(13):e2023008118. doi: 10.1073/pnas.2023008118.

IATA. 2021. "IATA - Net-Zero Carbon Emissions by 2050." Retrieved October 21, 2021 (https://www.iata.org/en/programs/sustainability/flynetzero/).

Kärcher, Bernd. 2018. "Formation and Radiative Forcing of Contrail Cirrus." *Nature Communications* 9(1):1824. doi: 10.1038/s41467-018-04068-0.

Klöwer, M., M. R. Allen, D. S. Lee, S. R. Proud, L. Gallagher, and A. Skowron. 2021. "Quantifying Aviation's Contribution to Global Warming." *Environmental Research Letters* 16(10):104027. doi: 10.1088/1748-9326/ac286e.

Köhler, M. O., G. Rädel, K. P. Shine, H. L. Rogers, and J. A. Pyle. 2013. "Latitudinal Variation of the Effect of Aviation NOx Emissions on Atmospheric Ozone and Methane and Related Climate Metrics." *Atmospheric Environment* 64:1–9. doi: 10.1016/j.atmosenv.2012.09.013.

Lee, D. S., D. W. Fahey, A. Skowron, M. R. Allen, U. Burkhardt, Q. Chen, S. J. Doherty, S. Freeman, P. M. Forster, J. Fuglestvedt, A. Gettelman, R. R. De León, L. L. Lim, M. T. Lund, R. J. Millar, B. Owen, J. E. Penner, G. Pitari, M. J. Prather, R. Sausen, and L. J. Wilcox. 2021. "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018." *Atmospheric Environment* 244:117834. doi: 10.1016/j.atmosenv.2020.117834.

Lee, David S., Myles R. Allen, Nicholas Cumpsty, Bethan Owen, Keith P. Shine, and Agnieszka Skowron. 2023. “Uncertainties in Mitigating Aviation Non-CO2 Emissions for Climate and Air Quality Using Hydrocarbon Fuels.” *Environmental Science: Atmospheres*. doi: 10.1039/D3EA00091E.

Lee, H., S. C. Olsen, D. J. Wuebbles, and D. Youn. 2013. “Impacts of Aircraft Emissions on the Air Quality near the Ground.” *Atmospheric Chemistry and Physics* 13(11):5505–22. doi: 10.5194/acp-13-5505-2013.

Linke, Florian, Volker Grewe, and Volker Gollnick. 2017. “The Implications of Intermediate Stop Operations on Aviation Emissions and Climate.” *Meteorologische Zeitschrift* 697–709. doi: 10.1127/metz/2017/0763.

Lund, Marianne T., Borgar Aamaas, Terje Berntsen, Lisa Bock, Ulrike Burkhardt, Jan S. Fuglestvedt, and Keith P. Shine. 2017. “Emission Metrics for Quantifying Regional Climate Impacts of Aviation.” *Earth System Dynamics* 8(3):547–63. doi: 10.5194/esd-8-547-2017.

van Manen, J., and V. Grewe. 2019. “Algorithmic Climate Change Functions for the Use in Eco-Efficient Flight Planning.” *Transportation Research Part D: Transport and Environment* 67:388–405. doi: 10.1016/j.trd.2018.12.016.

Märkl, Raphael Satoru, Christiane Voigt, Daniel Sauer, Rebecca Katharina Dischl, Stefan Kaufmann, Theresa Harlaß, Valerian Hahn, Anke Roiger, Cornelius Weiß-Rehm, Ulrike Burkhardt, Ulrich Schumann, Andreas Marsing, Monika Scheibe, Andreas Dörnbrack, Charles Renard, Maxime Gauthier, Peter Swann, Paul Madden, Darren Luff, Reetu Sallinen, Tobias Schripp, and Patrick Le Clercq. 2024. “Powering Aircraft with 100 % Sustainable Aviation Fuel Reduces Ice Crystals in Contrails.” *Atmospheric Chemistry and Physics* 24(6):3813–37. doi: 10.5194/acp-24-3813-2024.

Marks, Tobias, Katrin Dahlmann, Volker Grewe, Volker Gollnick, Florian Linke, Sigrun Matthes, Eike Stumpf, Majed Swaid, Simon Unterstrasser, Hiroshi Yamashita, and Clemens Zumegen. 2021. “Climate Impact Mitigation Potential of Formation Flight.” *Aerospace* 8(1):14. doi: 10.3390/aerospace8010014.

Maruhashi, Jin, Volker Grewe, Christine Frömming, Patrick Jöckel, and Irene C. Dedoussi. 2022. “Transport Patterns of Global Aviation NO_x and Their Short-Term O_3 Radiative Forcing – a Machine Learning Approach.” *Atmospheric Chemistry and Physics* 22(21):14253–82. doi: 10.5194/acp-22-14253-2022.

Maruhashi, Jin, Mariano Mertens, Volker Grewe, and Irene C. Dedoussi. 2024. “A Multi-Method Assessment of the Regional Sensitivities between Flight Altitude and Short-Term O3 Climate Warming from Aircraft NOx Emissions.” *Environmental Research Letters* 19(5):054007. doi: 10.1088/1748-9326/ad376a.

Matthes, Sigrun, Volker Grewe, Katrin Dahlmann, Christine Frömming, Emma Irvine, Ling Lim, Florian Linke, Benjamin Lührs, Bethan Owen, Keith Shine, Stavros Stromatas, Hiroshi Yamashita, and Feijia Yin. 2017. “A Concept for Multi-Criteria Environmental Assessment of Aircraft Trajectories.” *Aerospace* 4(3):42. doi: 10.3390/aerospace4030042.

Matthes, Sigrun, Ling Lim, Ulrike Burkhardt, Katrin Dahlmann, Simone Dietmüller, Volker Grewe, Amund S. Haslerud, Johannes Hendricks, Bethan Owen, Giovanni Pitari, Mattia Righi, and Agnieszka

Skowron. 2021. “Mitigation of Non-CO2 Aviation’s Climate Impact by Changing Cruise Altitudes.” *Aerospace* 8(2):36. doi: 10.3390/aerospace8020036.

Megill, Liam, Kathrin Deck, and Volker Grewe. 2024. “Alternative Climate Metrics to the Global Warming Potential Are More Suitable for Assessing Aviation Non-CO2 Effects.” *Communications Earth & Environment* 5(1):1–9. doi: 10.1038/s43247-024-01423-6.

Miller, Cassandra J., Prakash Prashanth, Florian Allroggen, Carla Grobler, Jayant S. Sabnis, Raymond L. Speth, and Steven R. H. Barrett. 2022. “An Environmental Cost Basis for Regulating Aviation NOx Emissions.” *Environmental Research Communications* 4(5):055002. doi: 10.1088/2515-7620/ac6938.

Mueller, Sean C., Neelakshi Hudda, Jonathan I. Levy, John L. Durant, Prasad Patil, Nina Franzen Lee, Ida Weiss, Tyler Tatro, Tiffany Duhl, and Kevin Lane. 2022. “Changes in Ultrafine Particle Concentrations near a Major Airport Following Reduced Transportation Activity during the COVID-19 Pandemic.” *Environmental Science & Technology Letters* 9(9):706–11. doi: 10.1021/acs.estlett.2c00322.

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, H. Zhang, D. Qin, G-k Plattner, M. Tignor, SK Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and PM Midgley. 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*. Cambridge United Kingdom and New York, NY, USA: Cambridge University Press.

Pandey, Gavendra, Akula Venkatram, and Saravanan Arunachalam. 2023. “Accounting for Plume Rise of Aircraft Emissions in AERMOD.” *Atmospheric Environment* 314:120106. doi: 10.1016/j.atmosenv.2023.120106.

Phoenix, Daniel, Arezoo Khodayari, Donald Wuebbles, and Kevin Stewart. 2019. “Aviation Impact on Air Quality Present Day and Mid-Century Simulated in the Community Atmosphere Model (CAM).” *Atmospheric Environment* 196:125–32. doi: 10.1016/j.atmosenv.2018.10.005.

Pletzer, Johannes, Didier Hauglustaine, Yann Cohen, Patrick Jöckel, and Volker Grewe. 2022. “The Climate Impact of Hydrogen-Powered Hypersonic Transport.” *Atmospheric Chemistry and Physics* 22(21):14323–54. doi: 10.5194/acp-22-14323-2022.

Ponater, Michael, Marius Bickel, Lisa Bock, and Ulrike Burkhardt. 2021. “Towards Determining the Contrail Cirrus Efficacy.” *Aerospace* 8(2):42. doi: 10.3390/aerospace8020042.

Ponater, Michael, Susanne Pechtl, Robert Sausen, Ulrich Schumann, and Gerhard Hüttig. 2006. “Potential of the Cryoplane Technology to Reduce Aircraft Climate Impact: A State-of-the-Art Assessment.” *Atmospheric Environment* 40(36):6928–44. doi: 10.1016/j.atmosenv.2006.06.036.

Prashanth, Prakash, Sebastian D. Eastham, Raymond L. Speth, and Steven R. H. Barrett. 2022. “Aerosol Formation Pathways from Aviation Emissions.” *Environmental Research Communications* 4(2):021002. doi: 10.1088/2515-7620/ac5229.

Prashanth, Prakash, Raymond L. Speth, Sebastian D. Eastham, Jayant S. Sabnis, and Steven R. H. H. Barrett. 2021. “Post-Combustion Emissions Control in Aero-Gas Turbine Engines.” *Energy & Environmental Science* 14(2):916–30. doi: 10.1039/d0ee02362k.

Quadros, Flávio D. A., Mirjam Snellen, and Irene C. Dedoussi. 2020. “Regional Sensitivities of Air Quality and Human Health Impacts to Aviation Emissions.” *Environmental Research Letters* 15(10):105013. doi: 10.1088/1748-9326/abb2c5.

Rao, Pratik, Feijia Yin, Volker Grewe, Hiroshi Yamashita, Patrick Jöckel, Sigrun Matthes, Mariano Mertens, and Christine Frömming. 2022. “Case Study for Testing the Validity of NOx-Ozone Algorithmic Climate Change Functions for Optimising Flight Trajectories.” *Aerospace* 9(5):231. doi: 10.3390/aerospace9050231.

Rennert, Kevin, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard G. Newell, William Pizer, Cora Kingdon, Jordan Wingenroth, Roger Cooke, Bryan Parthum, David Smith, Kevin Cromar, Delavane Diaz, Frances C. Moore, Ulrich K. Müller, Richard J. Plevin, Adrian E. Raftery, Hana Ševčíková, Hannah Sheets, James H. Stock, Tammy Tan, Mark Watson, Tony E. Wong, and David Anthoff. 2022. “Comprehensive Evidence Implies a Higher Social Cost of CO2.” *Nature* 610(7933):687–92. doi: 10.1038/s41586-022-05224-9.

Righi, Mattia, Johannes Hendricks, and Sabine Brinkop. 2023. “The Global Impact of the Transport Sectors on the Atmospheric Aerosol and the Resulting Climate Effects under the Shared Socioeconomic Pathways (SSPs).” *Earth System Dynamics* 14(4):835–59.

Sacchi, Romain, Viola Becattini, Paolo Gabrielli, Brian Cox, Alois Dirnaichner, Christian Bauer, and Marco Mazzotti. 2023. “How to Make Climate-Neutral Aviation Fly.” *Nature Communications* 14(1):3989. doi: 10.1038/s41467-023-39749-y.

Sausen, Robert, Sina Hofer, Klaus Gierens, Luca Bugliaro, Rüdiger Ehrmanntraut, Ilona Sitova, Kacper Walczak, Anja Burridge-Diesing, Milena Bowman, and Nick Miller. 2023. “Can We Successfully Avoid Persistent Contrails by Small Altitude Adjustments of Flights in the Real World?” *Meteorologische Zeitschrift* 102979. doi: 10.1127/metz/2023/1157.

Simone, Nicholas W., Marc E. J. Stettler, and Steven R. H. Barrett. 2013. “Rapid Estimation of Global Civil Aviation Emissions with Uncertainty Quantification.” *Transportation Research Part D: Transport and Environment* 25:33–41. doi: 10.1016/j.trd.2013.07.001.

Skowron, Agnieszka, David S. Lee, Rubén Rodríguez De León, Ling L. Lim, and Bethan Owen. 2021. “Greater Fuel Efficiency Is Potentially Preferable to Reducing NO x Emissions for Aviation’s Climate Impacts.” *Nature Communications 2021 12:1* 12(1):1–8. doi: 10.1038/s41467-020-20771-3.

Søvde, Ole Amund, Sigrun Matthes, Agnieszka Skowron, Daniela Iachetti, Ling Lim, Bethan Owen, Øivind Hodnebrog, Glauco Di Genova, Gianni Pitari, David S. Lee, Gunnar Myhre, and Ivar S. A. Isaksen. 2014. “Aircraft Emission Mitigation by Changing Route Altitude: A Multi-Model Estimate of Aircraft NOx Emission Impact on O3 Photochemistry.” *Atmospheric Environment* 95:468–79. doi: 10.1016/j.atmosenv.2014.06.049.

Staples, Mark D., Robert Malina, Hakan Olcay, Matthew N. Pearlson, James I. Hileman, Adam Boies, and Steven R. H. Barrett. 2014. “Lifecycle Greenhouse Gas Footprint and Minimum Selling Price of

Renewable Diesel and Jet Fuel from Fermentation and Advanced Fermentation Production Technologies." *Energy & Environmental Science* 7(5):1545–54. doi: 10.1039/C3EE43655A.

Stevenson, David S., Ruth M. Doherty, Michael G. Sanderson, William J. Collins, Colin E. Johnson, and Richard G. Derwent. 2004. "Radiative Forcing from Aircraft NOx Emissions: Mechanisms and Seasonal Dependence." *Journal of Geophysical Research* 109(D17):1–13. doi: 10.1029/2004JD004759.

Teoh, Roger, Ulrich Schumann, Arnab Majumdar, and Marc E. J. Stettler. 2020. "Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption." *Environmental Science & Technology* 54(5):2941–50. doi: 10.1021/acs.est.9b05608.

Terrenoire, E., D. A. Hauglustaine, T. Gasser, and O. Penanhoat. 2019. "The Contribution of Carbon Dioxide Emissions from the Aviation Sector to Future Climate Change." *Environmental Research Letters* 14(8):084019. doi: 10.1088/1748-9326/ab3086.

Terrenoire, Etienne, Didier A. Hauglustaine, Yann Cohen, Anne Cozic, Richard Valorso, Franck Lefèvre, and Sigrun Matthes. 2022. "Impact of Present and Future Aircraft NO_x and Aerosol Emissions on Atmospheric Composition and Associated Direct Radiative Forcing of Climate." *Atmospheric Chemistry and Physics* 22(18):11987–23. doi: 10.5194/acp-22-11987-2022.

Thoma, Evangelia Maria, Tomas Grönstedt, and Xin Zhao. 2020. "Quantifying the Environmental Design Trades for a State-of-the-Art Turbofan Engine." *Aerospace* 7(10):148. doi: 10.3390/aerospace7100148.

Turner, Michelle C., Michael Jerrett, C. Arden Pope, Daniel Krewski, Susan M. Gapstur, W. Ryan Diver, Bernardo S. Beckerman, Julian D. Marshall, Jason Su, Daniel L. Crouse, and Richard T. Burnett. 2016. "Long-Term Ozone Exposure and Mortality in a Large Prospective Study." *American Journal of Respiratory and Critical Care Medicine* 193(10):1134–42. doi: 10.1164/rccm.201508-1633OC.

Unterstrasser, Simon. 2020. "The Contrail Mitigation Potential of Aircraft Formation Flight Derived from High-Resolution Simulations." *Aerospace* 7(12):170. doi: 10.3390/aerospace7120170.

Vennam, L. P., W. Vizuete, K. Talgo, M. Omary, F. S. Binkowski, J. Xing, R. Mathur, and S. Arunachalam. 2017. "Modeled Full-Flight Aircraft Emissions Impacts on Air Quality and Their Sensitivity to Grid Resolution." *Journal of Geophysical Research: Atmospheres* 122(24):13,472-13,494. doi: 10.1002/2017JD026598.

Wang, Z. Juju, Mark D. Staples, Wallace E. Tyner, Xin Zhao, Robert Malina, Hakan Olcay, Florian Allroggen, and Steven R. H. Barrett. 2021. "Quantitative Policy Analysis for Sustainable Aviation Fuel Production Technologies." *Frontiers in Energy Research* 9.

Whitt, D. B., M. Z. Jacobson, J. T. Wilkerson, A. D. Naiman, and S. K. Lele. 2011. "Vertical Mixing of Commercial Aviation Emissions from Cruise Altitude to the Surface." *Journal of Geophysical Research: Atmospheres* 116(D14). doi: 10.1029/2010JD015532.

Yim, Steve H. L., Gideon L. Lee, In Hwan Lee, Florian Allroggen, Akshay Ashok, Fabio Caiazzo, Sebastian D. Eastham, Robert Malina, and Steven R. H. Barrett. 2015. "Global, Regional and Local Health Impacts of Civil Aviation Emissions." *Environmental Research Letters* 10(3):034001. doi: 10.1088/1748-9326/10/3/034001.

Yin, Feijia, Volker Grewe, Federica Castino, Pratik Rao, Sigrun Matthes, Katrin Dahlmann, Simone Dietmüller, Christine Frömming, Hiroshi Yamashita, Patrick Peter, Emma Klingaman, Keith P. Shine, Benjamin Lührs, and Florian Linke. 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):3313–34. doi: 10.5194/gmd-16-3313-2023.

Yin, Feijia, Volker Grewe, and Klaus Gierens. 2020. "Impact of Hybrid-Electric Aircraft on Contrail Coverage." *Aerospace* 7(10):147. doi: 10.3390/aerospace7100147.

Zengerling, Zarah Lea, Sara Dal Gesso, Florian Linke, Maximilian Clococeanu, Volker Gollnick, Patrick Peter, Sigrun Matthes, Baris Baspinar, Ibrahim Ozkol, Mahdi Noorafza, Paul Roling, Elena Branchini, Mattia Grampella, Carlo Abate, and Alessandra Tedeschi. 2023. "Operational Improvements to Reduce the Climate Impact of Aviation—A Comparative Study from EU Project ClimOP." *Applied Sciences* 13(16):9083. doi: 10.3390/app13169083.

Zhang, Jun, Donald Wuebbles, Douglas Kinnison, and Steven L. Baughcum. 2021. "Stratospheric Ozone and Climate Forcing Sensitivity to Cruise Altitudes for Fleets of Potential Supersonic Transport Aircraft." *Journal of Geophysical Research: Atmospheres* 126(16):e2021JD034971. doi: 10.1029/2021JD034971.