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Quantifying aviation's contribution to global warming

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Abstract

Growth in aviation contributes more to global warming than is generally appreciated because of the mix of climate pollutants it generates. Here, we model the CO_2 and non-CO_2 effects like nitrogen oxide emissions and contrail formation to analyse aviation's total warming footprint. Aviation contributed approximately 4% to observed human-induced global warming to date, despite being responsible for only 2.4% of global annual emissions of CO_2. Aviation is projected to cause a total of about 0.1 °C of warming by 2050, half of it to date and the other half over the next three decades, should aviation's pre-COVID growth resume. The industry would then contribute a 6%–17% share to the remaining 0.3 °C–0.8 °C to not exceed 1.5 °C–2 °C of global warming. Under this scenario, the reduction due to COVID-19 to date is small and is projected to only delay aviation's warming contribution by about five years. But the leveraging impact of growth also represents an opportunity: aviation's contribution to further warming would be immediately halted by either a sustained annual 2.5% decrease in air traffic under the existing fuel mix, or a transition to a 90% carbon-neutral fuel mix by 2050.

1. Introduction

Flying contributes to global warming. Through emissions and contrails, aircraft alter the radiative balance of the planet. Global aviation has increased dramatically in recent decades, from 310 million in 1970 to 4.3 billion passenger journeys in 2018 (International Air Transport Association 2020). The carbon footprint of top emitters in a society is usually dominated by air travel (Gore *et al* 2020), indicating the inherent inequality in this emission sector.

Aviation is a large international industry, important for business, governments, tourism, and research. Flying often provides the only possibility to reach remote locations within an acceptable time frame. However, flying is also one of the most carbon-intensive ways to travel, emitting per hour up to 100 times more than train, bus or shared car rides (Creutzig *et al* 2015). The public travels for a variety of reasons, essential journeys and leisure trips alike (Lenzen *et al* 2018). Since the beginning of the COVID-19 pandemic, many have involuntarily reduced travel, forcing the global aviation industry into its biggest economic crisis (Gössling 2020, International Air Transport Association 2020). In most countries, the majority of flights were cancelled from March 2020, simultaneously causing a large reduction in carbon emission and other climate pollutants (le Quéré *et al* 2020).

Limiting global warming to well below 2 °C requires all emission sectors to decarbonize and to present pathways that reach net zero in the second half of the 21st century (Intergovernmental Panel on Climate Change 2018). International aviation is usually considered a 'hard to abate' sector and often left out of reduction targets, as in the Paris Agreement (UK Climate Change Committee 2020, Grewe *et al* 2021). Before the pandemic, aviation was responsible for about 2.4% of global annual carbon emissions (Intergovernmental Panel on Climate Change

2015). Additionally, aircraft emissions of nitrogen oxides (NO_x) at altitudes of 8–12 km cause complex chemical reactions in the atmosphere as well as cirrus cloud formation through condensation trails (Lee *et al* 2021). To estimate aviation's contribution to current and future anthropogenic global warming, we analyse the total climate forcing, taking both CO_2 and non-CO_2 effects into account. Different scenarios are presented that depict possible futures of aviation until 2050, resulting in a discussion on the potential of various scenarios towards reducing aviation's contribution to global warming.

2. Methods

2.1. How aviation affects the climate

Aircraft engines have burned more than 1 billion litres of fuel per day in the years 2016–2019 before the pandemic (Lee *et al* 2021). In doing so, they emit, per kg of fuel, 3.16 kg of CO_2, 1.23 kg of water vapour (H_2O), up to 15.14 g of NO_x, 1.2 g of sulphur (SO_2) and 0.03 g of black carbon (soot), see table 1 in the appendix. Nitrogen oxides react in the atmosphere altering the radiative balance of other gases, including methane (CH_4), ozone (O_3) and stratospheric water vapour (H_2O) and therefore indirectly impact the climate. These non-CO_2 emissions cause an additional net warming effect (Lee *et al* 2009).

Aircraft can also create condensation trails on their paths, and if persistent, forming cirrus clouds that act as another climate forcing through reflection and absorption of radiation, net warming the planet (Chen and Gettelman 2013). Cloudiness is increased with contrails that scale approximately with the total distance flown. Airliners, i.e. excluding private, military and cargo flights, covered about 50 billion km in 2018 (Lee *et al* 2021), equivalent to 350 times the distance between the Earth and the Sun.

The emissions and persistent contrail formations are converted to effective radiative forcings (appendix, table 1), i.e. the additional energy that the Earth's surface receives on average through aircraft changing the atmospheric composition. The total climate forcing through all CO_2 and non-CO_2 effects is approximately their sum, assuming that the individual effects are independent of each other.

The contribution of any sector to global temperature change ΔT over period Δt is given, to a good approximation, by a combination of cumulative CO_2 emissions $\bar{E}\Delta t$ and cumulative non-CO_2 radiative forcing $\bar{F}\Delta t$ over that period (Intergovernmental Panel on Climate Change 2018, Smith *et al* 2021):

$$\Delta T = \chi\left(\bar{E}\Delta t + L^{-1}\bar{F}\Delta t\right) \qquad (1)$$

where χ is the *transient climate response to emissions* of about 0.45 °C per trillion tonnes of CO_2. The linear operator L converts CO_2 emission to radiative forcing using values from the IPCC 5th Assessment Report (Intergovernmental Panel on Climate Change 2015). Its inverse L^{-1} is used to convert non-CO_2 radiative forcing to CO_2 warming-equivalent emissions over multi-year time scales. The quantity in brackets is the total cumulative CO_2-warming-equivalent emissions (Cain *et al* 2019) over this period.

Here, we use data from the International Energy Agency (IEA) on jet fuel consumption and up-to-date assessments of non-CO_2 radiative forcing (Lee *et al* 2021) via the emission indices from table 1 (see appendix). The annual jet fuel consumption is translated to CO_2 emissions for each scenario. The radiative forcing of each non-CO_2 effect is summed and converted to warming-equivalent emissions using equation (1) which is supported with climate model simulations (Cain *et al* 2019, Smith *et al* 2021). For a given year, equation (1) effectively integrates CO_2 emissions and non-CO_2 radiative forcings from the past into the total warming footprint of aviation, using different time scales for both contributions. For details see the appendix.

2.2. Scenarios for 2050

Travel restrictions and national lockdowns due to the COVID-19 pandemic came into effect in 2020. Over Europe, many days in March and April 2020 saw fewer than 5000 flights, which is an 80% decrease from pre-COVID typical air traffic (figure 1). For summer 2020, European aviation partially recovered with more than 15 000 flights a day, only to face another decrease due to regional or national lockdowns in autumn and winter. Globally, the number of flights dropped by about 45% on average in 2020 (figure 2(b)).

Following the deployment of COVID-19 vaccines in 2021, air traffic is expected to increase again. Whether pre-COVID levels are reached within the next few years or whether international travel will remain low is unclear. Pandemic-induced travel restrictions could remain in case vaccines are not fully effective against some virus variants, and the boom in virtual technology could lower the demand for travel to meetings or conferences. Since 1970, aviation has grown at approximately 3% yr^{-1} (figure S1 (available online at stacks.iop.org/ERL/16/104027/mmedia)). We design four scenarios to capture possible futures of global aviation:

Scenario 1: No Pandemic assumes no COVID-19 pandemic and a continuous growth in air traffic CO_2 emissions of about 3% yr^{-1}. Annual growth data are taken from the International Civil Aviation Organization (see figure S1) assuming moderate efficiency improvements in technology and operation (Fleming and de Lépinay 2019).

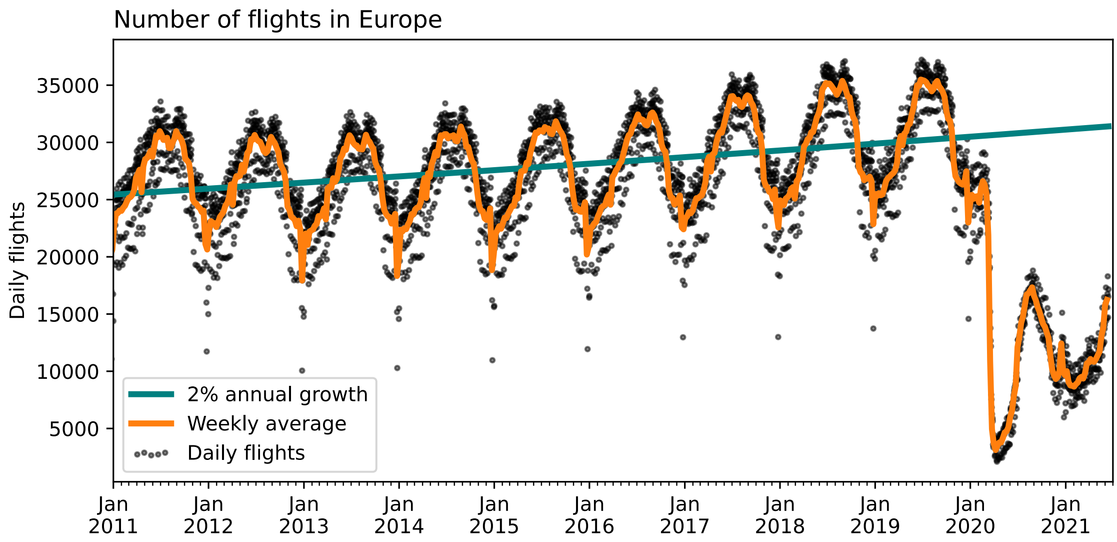

Figure 1. Daily flights over Europe between 2011 and present. The seasonal cycle shows more flights in summer and less in winter with a strong decrease associated with holidays at the end of the year. The number of flights increased by about 2% yr^{-1} pre-COVID in Europe. The pandemic forced many airplanes to ground since March 2020 with only a partial recovery in summer 2020 and 2021. Data from EUROCONTROL.

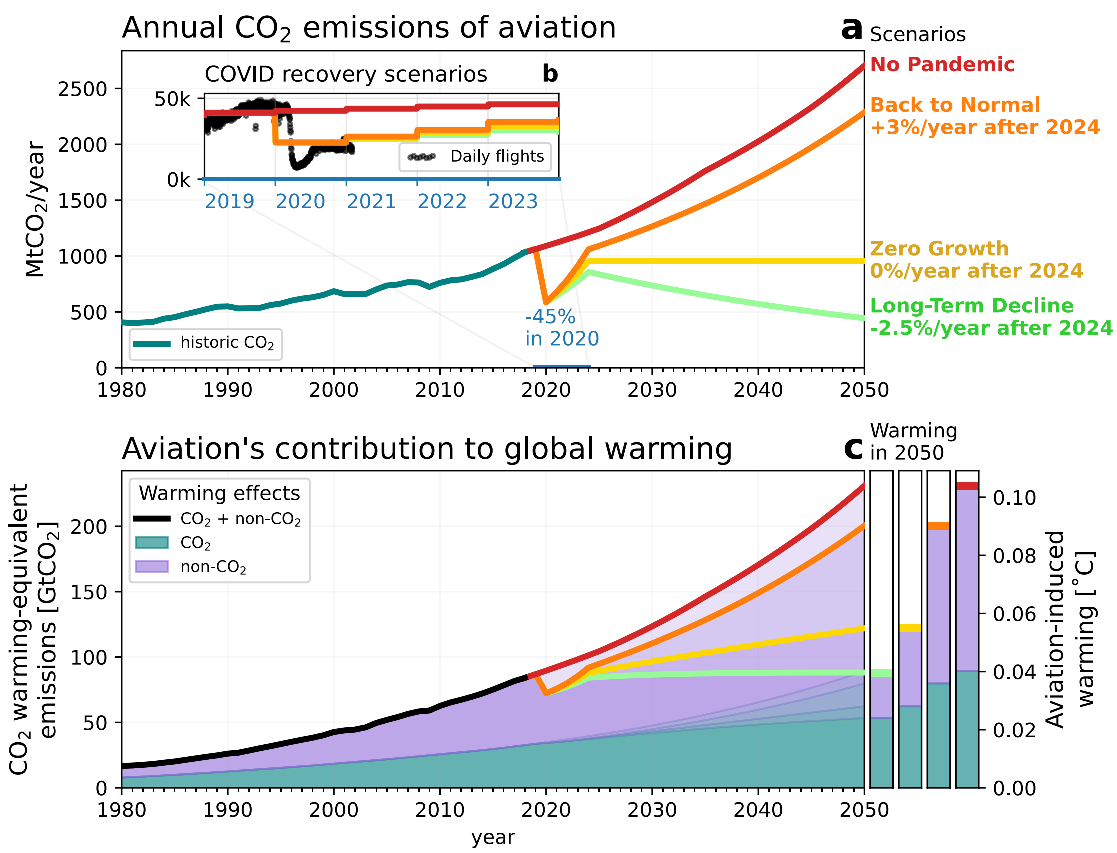

Figure 2. Aviation's contribution to global warming to 2050. (a) Annual historic and future annual carbon dioxide (CO_2) emissions of aviation following four scenarios: *No Pandemic*, *Back to Normal*, *Zero Long-Term Growth*, and *Long-Term Decline* as explained in the text. (b) Daily flights of selected airports globally between 2019 and November 2020 and annual averages for all scenarios. (c) Cumulative warming-equivalent emissions of CO_2 and non-CO_2 effects of aviation since 1940 and the corresponding aviation-induced global warming. Scenarios are colour-coded as in (a).

Scenario 2: Back to Normal assumes a post-COVID recovery for 2021–2024 at 16% annual growth and 3% thereafter. The pre-COVID level is reached in 2024.

Scenario 3: Zero Long-Term Growth assumes a 13% annual growth for the recovery period 2021–2024 and zero growth thereafter. About 90% of the pre-COVID level is reached in 2024.

Scenario 4: Long-Term Decline assumes a 10% annual growth for the recovery period 2021–2024 but a 2.5% yr^{-1} decline thereafter. Air traffic levels are about 50% lower in 2050 compared with 2019, similar to the first pandemic-year 2020.

Emissions indices are unchanged in these scenarios, and non-CO_2 climate forcings continue to scale with annual fuel consumption and hence CO_2 emissions. We convert the annual air traffic from these scenarios to jet fuel consumption, and subsequently to CO_2 emissions. Using equation (1) the warming footprint of aviation till 2050 is then obtained, prescribing only future changes in air traffic.

3. Results

3.1. Aviation's impact on global warming

In 2019 the emissions of global aviation were about 1 billion tonnes of CO_2 ($GtCO_2$), more than four times the emissions of New York City (Moran *et al* 2018). For the scenarios *No Pandemic* and *Back to Normal* with about 3% annual growth the emissions will more than double by 2050. In the other two scenarios the annual emissions peaked in 2019.

A large fraction of the increase in atmospheric CO_2 naturally stays for many 1000s of years (Inman 2008). Therefore not the recent emissions of CO_2 alone drive global warming, but the cumulative historic emissions. The accumulated carbon emissions of aviation for the period 1940–2019 are 33 $GtCO_2$ (figure S2(a)), equivalent to the historic emissions of Canada and about 2% of the world's CO_2 cumulative emissions. Through the climate forcing of these CO_2 emissions (figure S2(b)) a warming of 0.015 °C is already caused today, which will reach 0.025 °C–0.04 °C in 2050, depending on the scenario. COVID has had a negligible impact on the CO_2-induced warming from aviation until now, since it is the cumulative emissions that matter. Not negligible, however, is COVID's impact on the future of the aviation industry, with reasonable scenarios ranging from *Back to Normal* to *Long-Term Decline*. This scenario uncertainty will have a much bigger impact than the direct COVID-related reductions of CO_2 emission in 2020 and 2021.

Aircraft also affect the climate through other non-CO_2 climate pollutants, which have accounted for more than 50% of aviation-induced warming until 2020 (figure 2(c)). Contrails and contrail cirrus alone exerted a greater effective radiative forcing pre-COVID than that due to historic aviation CO_2 emissions (figure S3). These non-CO_2 effects act mostly within days (e.g. contrail cirrus) to decades (CH_4 response to NO_x). The long-term impacts of aviation therefore result from effects at different time scales: a large share of the CO_2 emissions are accumulated over centuries, while most non-CO_2 effects vanish within a year (the exception being the negative forcing from CH_4 perturbations). Taking both CO_2 and non-CO_2 effects into account, the total aviation-induced warming up to 2019 is about 0.04 ± 0.02 °C, about 4% of the almost 1.2 °C that the planet has warmed so far (Haustein *et al* 2017, Morice *et al* 2021). Aviation's 4% contribution to global warming is in good agreement with its 3.5% contribution to the effective radiative forcing (Lee *et al* 2021). About 0.03 °C of the aviation-induced warming is due to emissions since 1990, representing 5.3% of total human-induced warming in this period.

How much warming will aviation have caused in 2050? Following the 3% annual growth scenario *Back to Normal*, aviation will have contributed 0.09 ± 0.04 °C to global warming by 2050 (figure 2). More than half of that warming will be caused in the next three decades, contributing a 6%–17% share to the remaining 0.3 °C–0.8 °C to stay within a 1.5 °C–2 °C target. Without policy intervention, this contribution will continue to increase beyond 2050. While the halt in air traffic due to COVID in 2020 alone has a small impact, COVID's presumably long-lasting impact on the aviation industry is crucial. The recovery period will delay aviation-induced warming, reducing it by about 10% in 2050. The annual growth in air traffic in the coming years and decades has therefore a much greater impact than COVID in 2020 and 2021. In that sense, COVID is projected to only delay the warming contribution of aviation by about five years, should the pre-COVID growth resume. In the *Zero Long-Term Growth* scenario aviation-induced warming will keep rising over the next decades, as the CO_2 emissions continue to accumulate and start to dominate over the non-CO_2 effects.

Interestingly, if global aviation were to decline by about 2.5% yr^{-1}, even with no change in current fuel mix or flight practices, the impacts of the continued rise in accumulated CO_2 emissions and the fall of non-CO_2 climate forcers would balance each other, leading to no further increase in aviation-induced warming with immediate effect. As a comparison, ambitious climate targets require other sectors to reduce emissions by 3%–8% yr^{-1} (Intergovernmental Panel on Climate Change 2018), still implying a significant continuous contribution to further warming over the next decades. The short-lived climate forcers, which amplify the impact of any

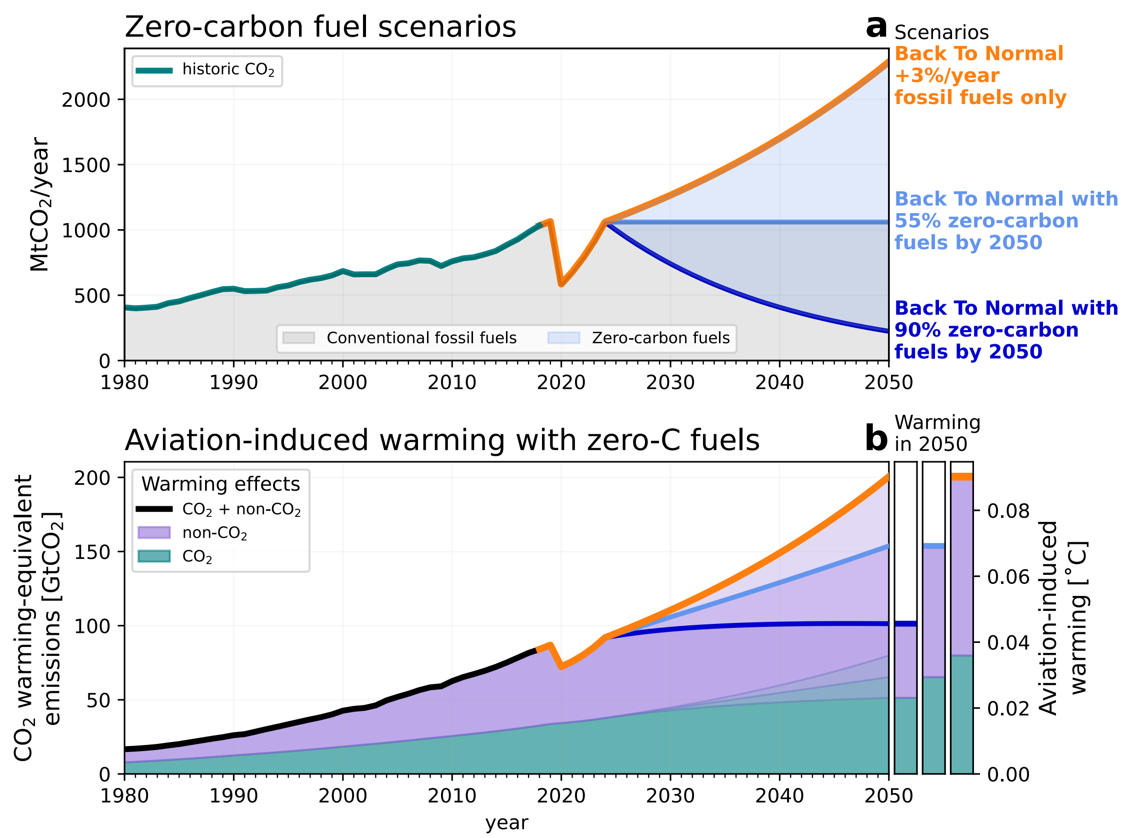

Figure 3. Zero-carbon fuels (bio or synthetic) can limit aviation-induced warming only when they replace fossil fuels by 2050. (a) CO_2 emissions of aviation following the 3% annual air traffic growth of the *Back to Normal* scenario (as in figure 1) but with increasing use of zero-carbon fuels. (b) Aviation-induced warming in two scenarios: 55% zero-carbon fuels by 2050 will not limit the warming, only the highly ambitious scenario of 90% carbon neutrality reaches a maximum warming of about 0.04 °C. Scenarios are colour-coded as in (a).

increase in aviation emissions, however, also act to amplify the impact of any decrease. Consequently, aviation would not actually need to cease immediately to end its contribution to further global warming—an optimistic message given the limited options of near-operational alternatives to carbon-intensive intercontinental flights.

3.2. Potential of zero-carbon fuels

If 3% yr^{-1} growth continues, the most obvious remaining option to reduce aviation's CO_2 emissions is rapid introduction of low-carbon fuel (bio or synthetic) as an alternative to conventional fossil-based jet fuel. Carbon emissions are compensated for (at least partially) during the growth-phase of respective plants, or in the extraction of CO_2 from the air for the production of synthetic fuels, if renewable energy is used (Yao *et al* 2020). Although low-carbon fuels are unlikely to be fully carbon neutral, for simplicity we will only consider here the effective carbon neutrality of the fuel mix. To capture the impact that such idealized zero-carbon fuels would have on aviation-induced warming we design the following additional scenarios.

Scenario 5: 55% zero-carbon fuels by 2050 assumes an air traffic growth following the *Back to Normal* scenario, but with a 3% increase of zero-carbon fuels per year from 2024. The increased CO_2 emissions from increased air traffic are therefore compensated, resulting in constant annual emissions at pre-COVID levels. By 2050 the fuel mix is 55% zero-carbon.

Scenario 6: 90% zero-carbon fuels by 2050 makes the same assumptions as scenario *55% zero-carbon fuels by 2050* but with an annual 5.8% increase of zero-carbon fuels. The increased CO_2 emissions from increased air traffic are therefore overcompensated, lowering annual CO_2 emissions over time. By 2050 the fuel mix is 90% zero-carbon.

While for scenarios 5 and 6 with zero-carbon fuels the CO_2 emission indices are respectively lowered, the non-CO_2 climate forcings continue to scale with annual fuel consumption (regardless of the carbon neutrality of the fuel mix). However, due to fewer soot particles in bio or synthetic fuels contrail formation is predicted to be reduced by low-carbon fuels (Burkhardt *et al* 2018,

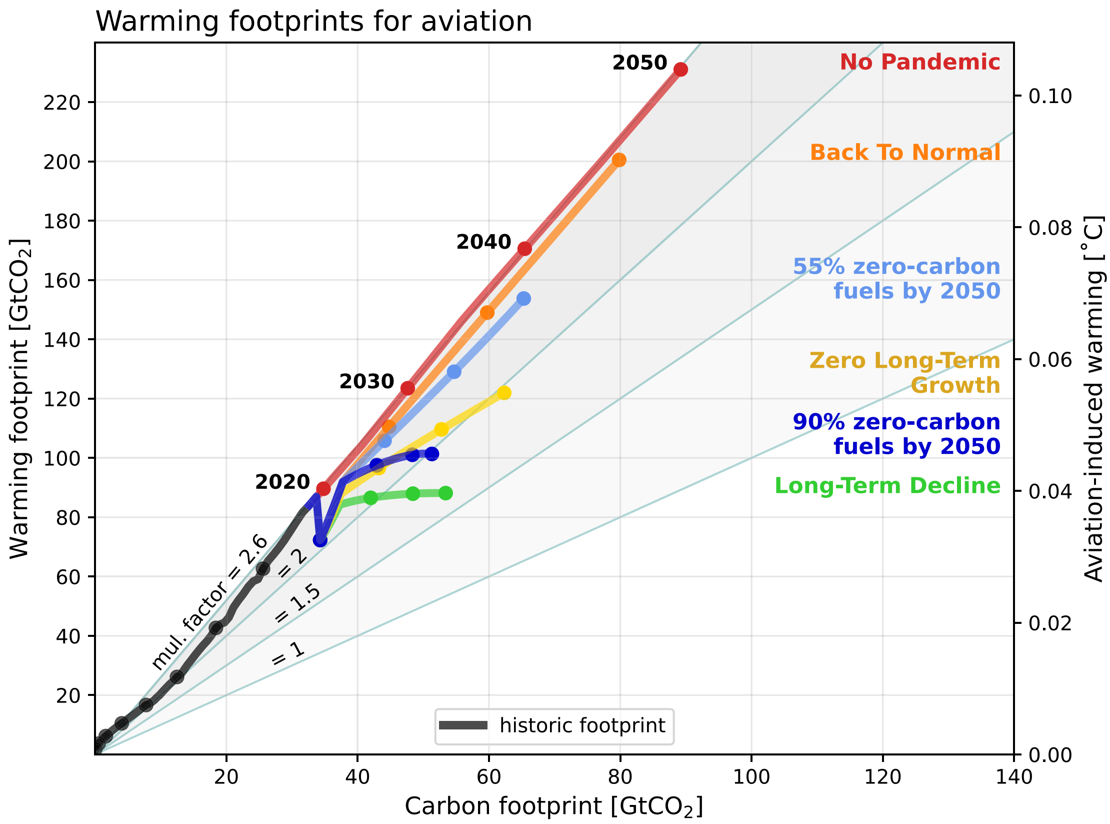

Figure 4. The warming footprint of aviation is a scenario and time-dependent multiplicative of its cumulative carbon footprint, about 2–2.6× larger in recent decades. Diagonal lines represent a constant *multiplication factor* often used in carbon footprint analyses to simplify the non-CO_2 effects of aviation. Dots represent decades for all scenarios and historic emissions. Warming footprints are the cumulative CO_2 warming-equivalent emissions, including both CO_2 and non-CO_2 effects.

Kärcher *et al* 2021, Voigt *et al* 2021). We parametrize this effect as explained in the appendix.

Changes in flight routes can also alter non-CO_2 effects. For example, adjusting aircraft cruise altitude can reduce the formation of contrails and hence the associated radiative forcing, by up to 60% (Teoh *et al* 2020). However, additional CO_2 emissions may be incurred and persistent contrail formation cannot yet be predicted with sufficient accuracy. Hydrogen fuels are another possible alternative, but not considered here due to limited data on their non-CO_2 effects.

The *Back to Normal* scenario with an increasing use of low-carbon fuels, reaching 55% carbon-neutrality by 2050 (similar to IEA's *Sustainable Development Scenario*, IEA 2020), is investigated (figure 3). Such a scenario will reduce aviation's contribution to global warming insufficiently to be sustainable, nor will it stop the non-CO_2 effects from increasing. Only a much more ambitious 90% carbon-neutral fuel-mix by 2050 will limit aviation-induced warming. Low-carbon fuels also need to compete with food crops to be sustainable, and emissions from land-use change need to be considered too.

3.3. Warming footprints instead of carbon footprints

Many carbon footprint calculators use a constant, so-called *multiplication factor* to include the non-CO_2 effects of aviation in a simplified way. For a 3% continuous annual growth in aviation the multiplication factor is approximately 2.6, such that the aviation-induced warming is 2.6 times greater than from its carbon emissions alone (figure 4). In general, multiplication factors are scenario and time-dependent and therefore should be used with caution in carbon footprint calculations. Nevertheless, for all scenarios the warming footprint of aviation is at least twice as large as its carbon footprint in the coming decade, clearly highlighting that non-CO_2 effects are non-negligible to assess the contribution of aviation to global warming.

4. Discussion

In conclusion, a significant on-going reduction of 2.5% yr^{-1} in aviation CO_2 emissions limits the aviation sector's contribution to further global warming. This scenario captures a future in which air traffic in 2050 is reduced to about 50% compared to pre-COVID levels—similar to summer 2020 and 2021. While this scenario is possible, its realism over the next decades highly depends on climate policy measures like kerosene taxes, on-going pandemic-related travel restrictions, air passenger behaviour and the economics within the aviation industry.

Alternatively, or in combination with air traffic reductions, low-carbon fuels could replace fossil fuels over the next decades—a strategy that has to be treated with caution, as non-CO_2 climate impacts of alternative fuels are less well understood (Burkhardt *et al* 2018). Planning on fuel efficiency improvements does not significantly reduce aviation's contribution to warming, as past progress in efficiency was over-compensated by air traffic growth and further efficiency potential is limited. More efficient jet engines tend to produce more contrails, such that savings in fuel could be overcompensated by the warming effect of contrails (Schumann 2000).

The pandemic has forced us to limit international travel—is this an opportunity to reevaluate the structures within aviation and to rethink its possible future? Such a reevaluation would benefit from greater clarity about how aviation actually contributes to changing global temperatures, a link that is currently obscured by conventional 'carbon footprint' metrics. Expressing the impact of aviation in terms of warming-equivalent emissions (the 'warming footprint') makes this link clearer, and also reveals that a decline of 2.5% yr^{-1} would be consistent with no additional aviation-induced warming. Rapid introduction of low-carbon fuels, provided these are themselves sustainable, can support this.

The pandemic and a boom in virtual technology has led many to question the necessity of flying. Nevertheless, mobility is an essential aspect of a globalized society, which has to be decoupled from aviation's climate impact to mitigate the climate crisis. The powerful leveraging effect of non-CO_2 climate drivers means this could be achieved surprisingly rapidly through a 2.5% yr^{-1} contraction over the coming decades, buying time to develop fully sustainable solutions.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.5534138.

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Conflict of interest

The authors declare no competing financial interests to influence this work.

Appendix

1. Flight data

The European flight history data shown in figure 1 were extracted from the European Organisation for the Safety of Air Navigation (EUROCONTROL) STATFOR system and is copyright by EUROCONTROL, 2021. It includes all civilian aircraft required to file flight plans in European airspace each day. The daily flight data in figure 2(b) were derived from the OpenSky database (Schäfer *et al* 2014, Strohmeier *et al* 2021). Aircraft positions were downloaded and processed into individual flights by detecting take-off and landings (Proud 2020).

The annual fuel consumption of aviation and the data of total distance covered per year are from Lee *et al* (2021) originally derived from International Energy Agency (IEA) data on JET-A fuel usage and aviation gasoline. Data on aviation's CO_2 emissions dating back to 1940 is taken from Sausen and Schumann (2000). The No Pandemic scenario uses data from the International Energy Agency (IEA) which is subject to copyright and cannot be shared. Figure S1 illustrates that data and shows how it can be well approximated for reproducibility.

2. Effective radiative forcings

Based on the annual fuel consumption of aviation, the emissions of CO_2 and other greenhouse gases and aerosols are calculated following the emission indices from table 1, which are the best estimate from Lee *et al* (2021).

The emissions indices for CO_2 and water vapour are fixed for fossil fuel. The emission index for NO_x has been increasing from 9.8 g kg^{-1} fuel in 1980 over to a value of 15.14 g kg^{-1} fuel in 2018 and is not assumed to increase further. The emission index for sulfur (S) is dependent on the fuel's sulfur content, which is only poorly known but is assumed to have an average of 600 ppm by volume. Soot emission indices are only very poorly known. Further documentation on these emission indices and the data quality/sources of information can be found in Lee *et al* (2021). The total non-CO_2 effective radiative forcing $F_{\text{non - }CO_2}$ is approximately the arithmetic sum of the individual components (Lee *et al* 2021)

Table 1. Best estimate emission indices and effective radiative forcing for aviation emissions and contrail formation from Lee *et al* (2021). Effective radiative forcings from NO_x arise via reaction with CH_4, O_3 (short and long-term) and stratospheric water vapour and are noted therein. Consequently, the radiative forcings of these scale with the emission of NO_x.

	Emission index (per kg fuel)	Effective radiative forcing
Carbon dioxide CO_2	3.16 kg	(From climate model)
Water vapour H_2O	1.231 kg	0.0052 mW m^{-2} (Tg (H_2O) $yr^{-1})^{-1}$
Black carbon (BC)	0.03 g	100.67 mW m^{-2} (Tg (BC) $yr^{-1})^{-1}$
Sulphate SO_2	1.2 g	−19.91 mW m^{-2} (Tg (SO_2) $yr^{-1})^{-1}$
Nitrogen oxides NO_x	15.14 g (in 2018)	(Via CH_4, O_3 and strat. H_2O)
Methane CH_4 decrease	—	−18.69 mW m^{-2} (Tg (N) $yr^{-1})^{-1}$
Ozone O_3 short-term increase	—	34.44 mW m^{-2} (Tg (N) $yr^{-1})^{-1}$
Ozone O_3 long-term decrease	—	−9.35 mW m^{-2} (Tg (N) $yr^{-1})^{-1}$
Stratospheric H_2O (SWV) decrease	—	−2.8 mW m^{-2} (Tg (N) $yr^{-1})^{-1}$
Contrail cirrus	—	9.36×10^{-10} mW m^{-2} km^{-1}

$$F_{\text{non - CO}_2} = F_{\text{H}_2\text{O}} + F_{\text{BC}} + F_{\text{SO}_2} + F_{\text{CH}_4} + F_{\text{O}_3\text{short}} + F_{\text{O}_3\text{long}} + F_{\text{SWV}} + F_{\text{contrail}}. \quad (2)$$

The annual effective radiative forcings $F(t)$ for non-CO_2 are extrapolated for time t in years into the future under a p-percent growth model as follows

$$F(t) = F_0\left(1 + \frac{p}{100}\right)^{t-t_0} \quad (3)$$

with F_0 being the initial forcing at the start t_0 of the scenario.

3. Radiative forcing of CO_2

Using the finite amplitude impulse response climate model (Smith *et al* 2018), the carbon emissions of aviation are converted to a radiative forcing, which amounts to 32.6 mW m^{-2} in 2018 (figure S2(b)), about 2% of the total anthropogenic forcing from CO_2 (Intergovernmental Panel on Climate Change 2015). As a baseline we use the Representative Concentration Pathways (RCP) 2.6, 4.5 and 6.0, and attribute the CO_2 radiative forcing from aviation by subtracting aviation emissions from the baseline CO_2 emissions. The effective radiative forcing for CO_2 is then taken as the average of the three scenarios RCP 2.6, 4.5 and 6.0.

4. Warming-equivalent emissions

For F in equation (1) the sum of the effective radiative forcings of non-CO_2 effects (figure S2(b)) is used, assuming independence of the different effects (e.g. the aircraft impact of NO_x is sensitive to the chemistry of the background atmosphere (Skowron *et al* 2021), here the future atmosphere is assumed to be the mean of the three RCP scenarios).

The year 1940 is taken as the start of commercial aviation, such that the considered time period is $\Delta t = t - 1940$. The linear operator L is a lower triangular Toeplitz matrix integrating the CO_2 emissions since 1940 to effective radiative forcing in year t with exponentially decaying weights (e-folding time scale is about 200 years) for years further in the past. Applying its inverse to the time series of cumulative non-CO_2 radiative forcing $\bar{F}\Delta t$ therefore returns the cumulative CO_2 that would cause the same warming on a multi-year time scale. For further information see Smith *et al* (2021).

5. Zero-carbon fuels

Alternative fuels from bio or power to liquid sources have a very small change in emission indices with a different overall C/H ratio to fossil kerosene, but are considered to be insignificant for the purposes of this work. Low-carbon fuels tend to reduce contrail formation through soot particles. We parametrize this effect based on Burkhardt *et al* (2018) (figure 1(f) therein) to reduce the radiative forcing F_{contrail} by

$$F^*_{\text{contrail}} = \sqrt{m}F_{\text{contrail}} \quad (4)$$

where $1 - m$ is the effective share of zero-carbon fuels in the fuel mix. The average CO_2 emission index of 3.16 kg kg^{-1} of fuel (table 1) is effectively reduced to $3.16m$ kg kg^{-1} of fuel. Zero-carbon fuels are assumed to be fully carbon-neutral.

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