Quantifying aviation's contribution to global warming

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Growth in aviation contributes more to global warming than is generally appreciated because of the mix of climate pollutants it generates: 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 have caused 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 will contribute a 6-17% share to the remaining 0.3-0.8˚C to not exceed 1.5-2˚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 5 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 flights under the existing fuel mix, or a transition to a 90% carbon-neutral fuel mix by 2050.

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, Alestig, and Ratcliff 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 of us have involuntarily reduced travel, forcing the global aviation industry into its biggest economic crisis (International Air Transport Association 2020; Gössling 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 decarbonise and to present pathways that reach net zero in the second half of the 21^{st} 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 Commitee 2020). Before the pandemic, aviation was responsible for about 2.4% of global annual carbon emissions (Intergovernmental Panel on Climate Change 2015). Additionally, aircraft mostly emit nitrogen oxides (NO_x) at altitudes of 8 - 12 km, causing complex chemical reactions in the atmosphere as well as causing cirrus cloud formation through condensation trails (David S. Lee et al. 2020). 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 how the aviation industry can act.

How aviation affects the climate

Aircraft engines have burned more than 1 billion litres of fuel per day in recent years(David S. Lee et al. 2020). 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 S1. 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 (David S. Lee et al. 2020).

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 (David S. Lee et al. 2020), equivalent to 350 times the distance between the Earth and the Sun.

The emissions and persistent contrail formations are converted to effective radiative forcings (Table S1), 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 (M. Smith, Cain, and Allen 2021; Intergovernmental Panel on Climate Change 2018):

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

Where χ is the *transient climate response to emissions* (TCRE) 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 up-to-date assessments of non-CO_2 radiative forcing (David S. Lee et al. 2020) expressed as warming-equivalent emissions using the above formula. For details see the supplementary information.

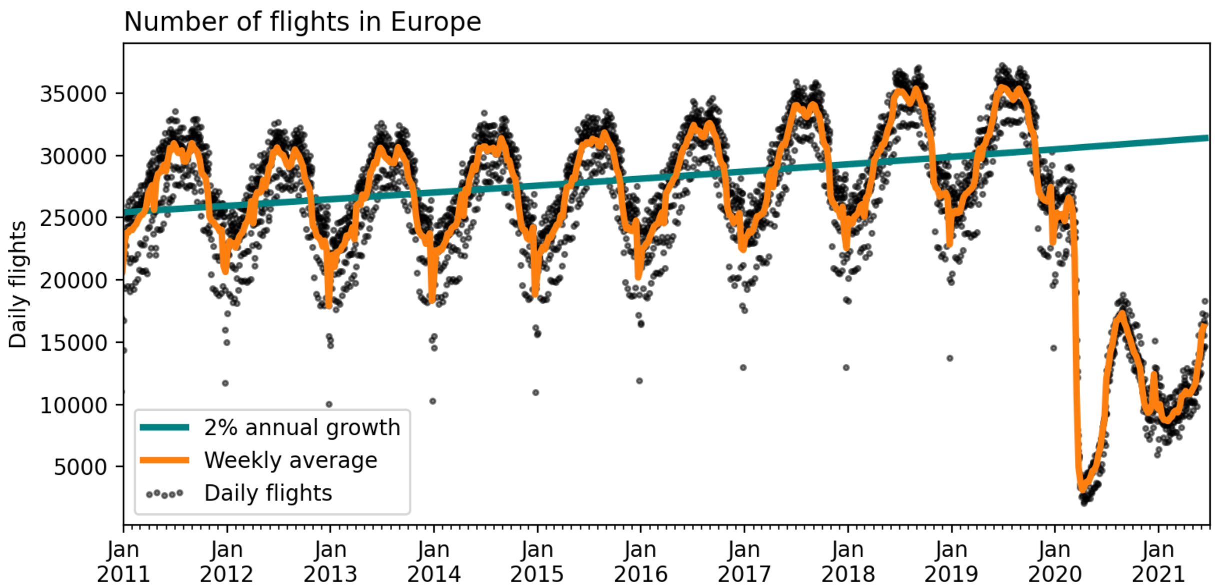

Figure 1. Daily flights over Europe between 2011 and present. The seasonal cycle shows more flights in summer and less in winter with a strong decrease associated with holidays at the end of the year. The number of flights increased by about 2% per year pre-COVID in Europe. The pandemic forced many airplanes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

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 5,000 flights, which is an 80% decrease from pre-COVID typical air traffic (Fig. 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 (Fig. 2b).

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% per year (Fig. S1). 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% per year. Annual growth data are taken from the International Civil Aviation Organization (ICAO, see Fig. S1) assuming moderate efficiency improvements in technology and operation (Fleming and de Lépinay 2019).

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% per year 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 scenarios, and non-CO_2 climate forcings continue to scale with annual CO_2 emissions.

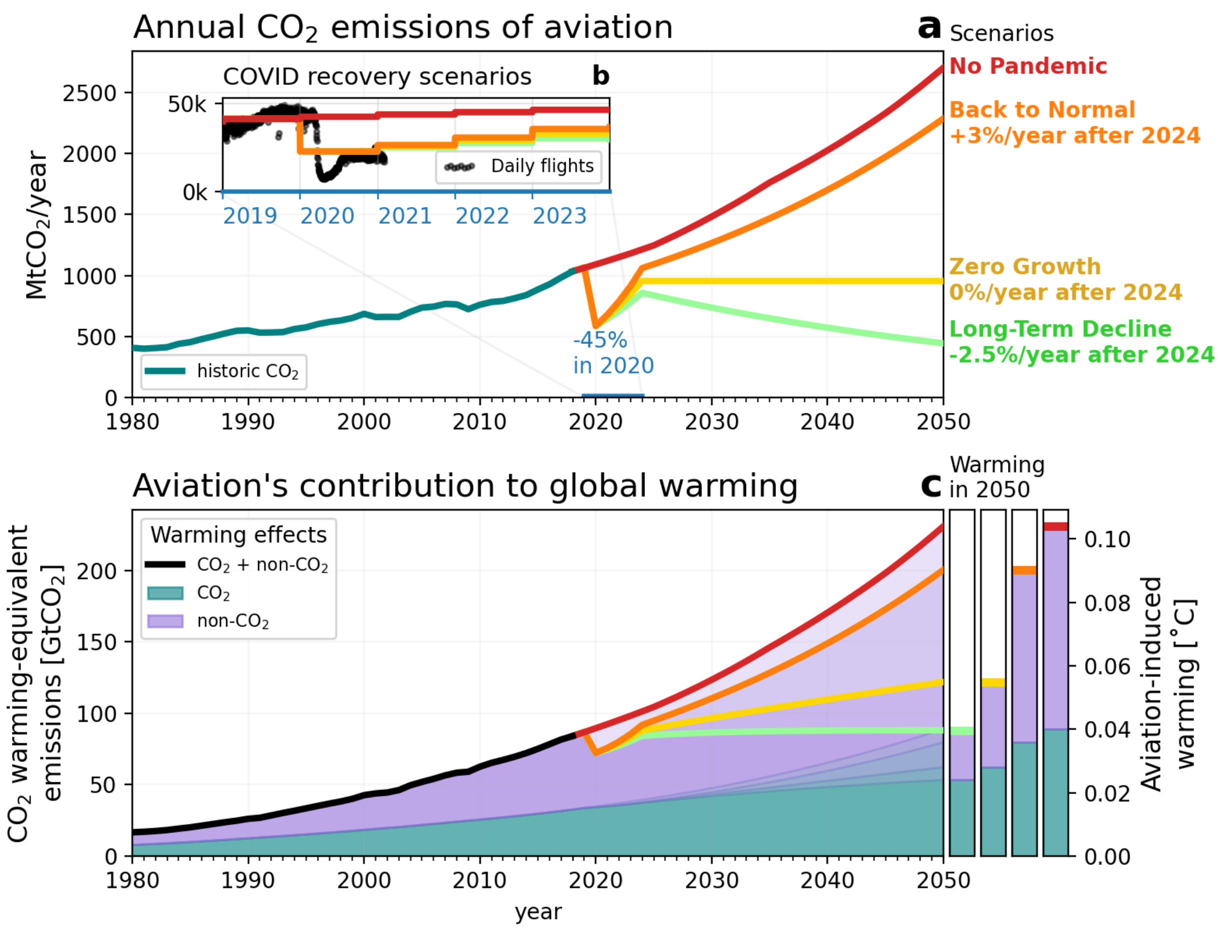

Figure 2. Aviation's contribution to global warming to 2050. **a** Annual historic and future annual carbon dioxide (CO_2) emissions of aviation following four scenarios: *No Pandemic, Back To Normal, Zero Long-Term Growth,* and *Long-Term Decline* as explained in the text. **b** Daily flights of selected airports globally between 2019 and Nov 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**.

Aviation's warming footprint

In 2019 the emissions of global aviation were about 1 billion tonnes of CO_2 ($GtCO_2$), more than 4 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 1,000s 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 (Fig. S2a), 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 (Fig. S2b) a warming of 0.015˚C is already caused today, which will reach 0.025-0.04˚C in 2050, depending on the scenario. COVID has a negligible impact on the CO_2-induced warming from aviation, since it is the cumulative emissions that matter. However, aircraft also affect the climate through other climate pollutants. Contrails and contrail cirrus alone exerted a greater effective radiative forcing pre-COVID than that due to historic aviation CO_2 emissions (Fig. 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 accumulated past CO_2 emissions but from the recent non-CO_2 effects. Taking both 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). This is in good agreement with the Effective Radiative Forcing fraction of 3.5% (David S. Lee et al. 2020). About 0.03°C of this 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 (Fig. 2). More than half of that warming will be caused in the next three decades, contributing a 6-17% share to the remaining 0.3-0.8˚C to stay within a 1.5-2˚C target. Without policy intervention, this contribution will continue to increase beyond 2050. The halt in air traffic due to COVID in 2020 will reduce this only slightly, by ~10%. The annual growth in air traffic in the coming years has a much greater impact than COVID itself. In that sense, COVID is projected to only delay the warming contribution of aviation by about 5 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% per year, 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% per year[15], still implying a significant continuous contribution to further warming over the next decades. The short-lived climate forcers, which amplify the impact of any 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.

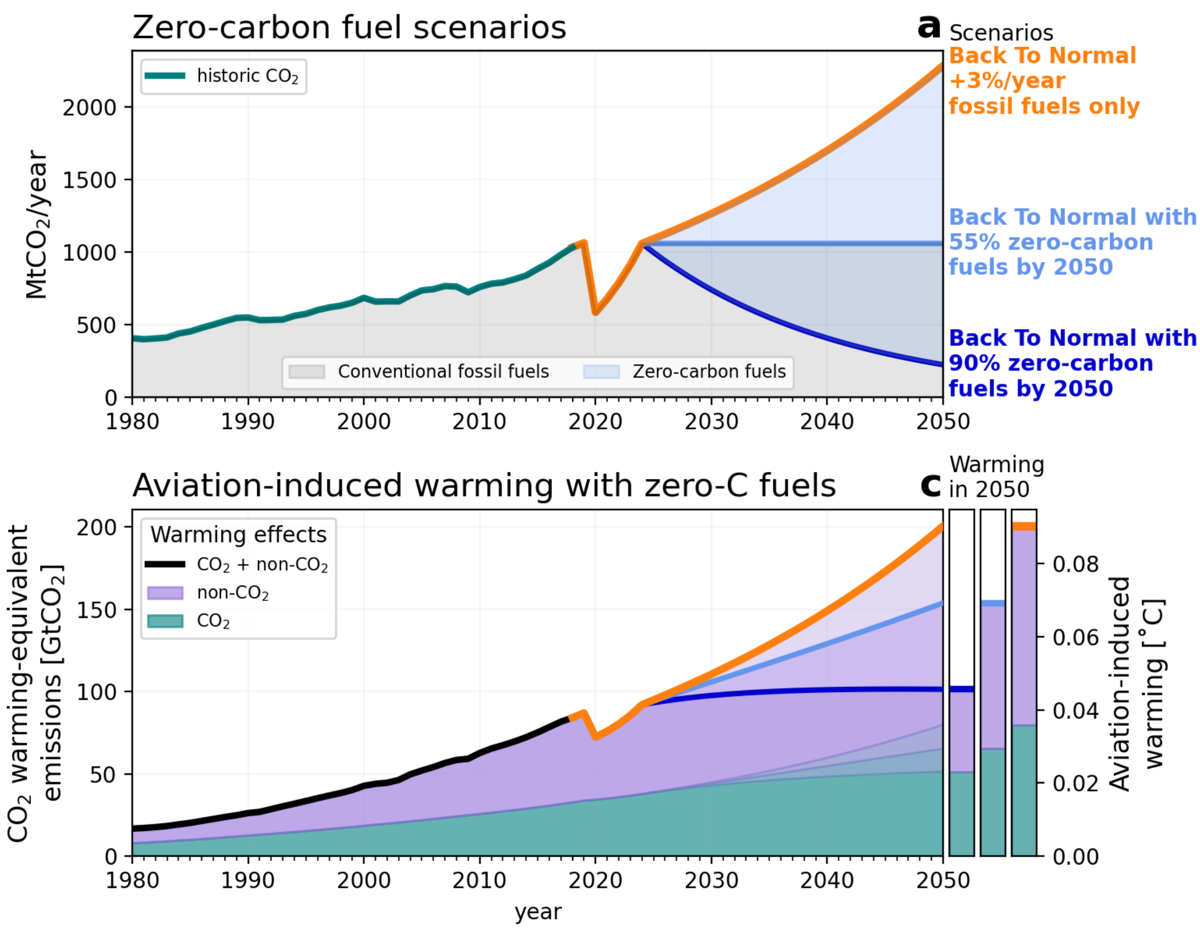

Figure 3. Zero-carbon fuels (bio or synthetic) can limit aviation-induced warming only when they replace fossil fuels by 2050. **a** CO_2 emissions of aviation following the 3% annual air traffic growth of the *Back To Normal* scenario (as in Figure 1) but with increasing use of zero-carbon fuels. **b** 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**.

Potential of zero-carbon fuels

If 3% per year 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 most non-CO_2 effects would continue to increase warming with increasing air traffic, contrail formation is predicted to be reduced by low-carbon fuels (Burkhardt, Bock, and Bier 2018; Voigt et al. 2021; Kärcher, Mahrt, and Marcolli 2021), see supplement. 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 its 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.

Many carbon footprint calculators use a constant, so-called *multiplication factor* to include the non-CO_2 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 (Fig. 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.

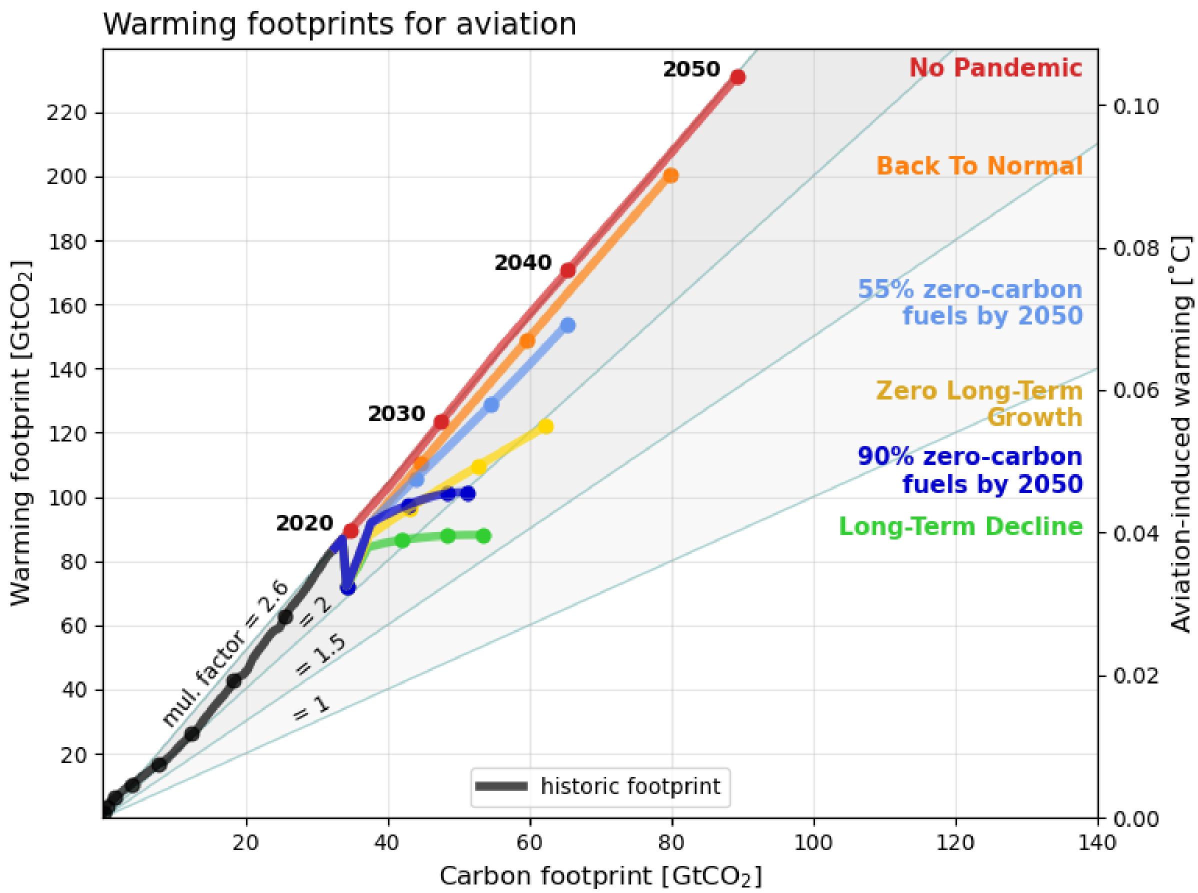

Figure 4. The warming footprint of aviation is a scenario and time-dependent multiplicative of its cumulative carbon footprint, about 2-2.6x larger in recent decades. Diagonal lines represent a constant *multiplication factor* often used in carbon footprint analyses to simplify the non-CO_2 effects of 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.

Future of aviation

In conclusion, a significant on-going reduction of 2.5% per year in aviation CO_2 emissions limits the aviation sector's contribution to further global warming. Alternatively, or in combination, 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, Bock, and Bier 2018). Planning on fuel efficiency improvements does not significantly reduce aviation's contribution to warming, as past progress in efficiency was overcompensated 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 makes this link clear, and also reveals that a decline of 2.5% per year 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 globalised 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% per year contraction over the coming decades, buying time to develop fully sustainable solutions.

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Declaration of competing interest

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

Data and materials availability

All data are available in https://github.com/milankl/FlyingClimate (will be converted to DOI upon acceptance) and described in the supplementary information. Only the No Pandemic scenario uses data from the International Energy Agency (IEA) which is subject to copyright and cannot be shared. Fig. S1 illustrates that data and shows how it can be well approximated for reproducibility. European flight history data are retrieved from the European Organisation for the Safety of Air Navigation (EUROCONTROL) STATFOR dashboard and is copyright by EUROCONTROL, 2020.

Appendix

1. Flight data

The European flight data shown in Fig. 1 were extracted from the EUROCONTROL STRATFOR system and includes all civilian aircraft required to file flight plans in European airspace each day. The daily flight data in Figure 2b were derived from the Opensky database (Strohmeier et al. 2021; Schäfer et al. 2014). 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. 2020 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 (Sausen and Schumann 2000).

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. 2020.

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

Table 1: Best estimate emission indices and effective radiative forcing for aviation emissions and contrail formation from Lee et al. 2020. 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.

The emissions indices for CO_2 and water vapour are fixed for fossil fuel. The emission index for NO_x has been increasing from 9.8g/kg fuel in 1980 over to a value of 15.14 g/kg fuel in 2018 and is not assumed to increase further. The emission index for S is dependent on the fuel S 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. (2020). The total non-CO_2 effective radiative forcing $F_{\text{non-CO}_2}$ is approximately the arithmetic sum of the individual components (David S. Lee et al. 2020)

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

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

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

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 (FaIR) climate model (C. J. 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 (Fig. S2b), about 2% of the total anthropogenic forcing from CO_2 (Intergovernmental Panel on Climate Change 2015). As a baseline we use RCP2.6, 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 RCP2.6, 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 (Fig. S2b) 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 Representative Concentration Pathways scenarios[8]).

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 (M. Smith, Cain, and Allen 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 (Fig. 1f therein) to reduce the radiative forcing F_contrail by

$$F^*_\text{contrail} = \sqrt{m} F_\text{contrail} \tag{5}$$

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

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Supplementary Information

Figures

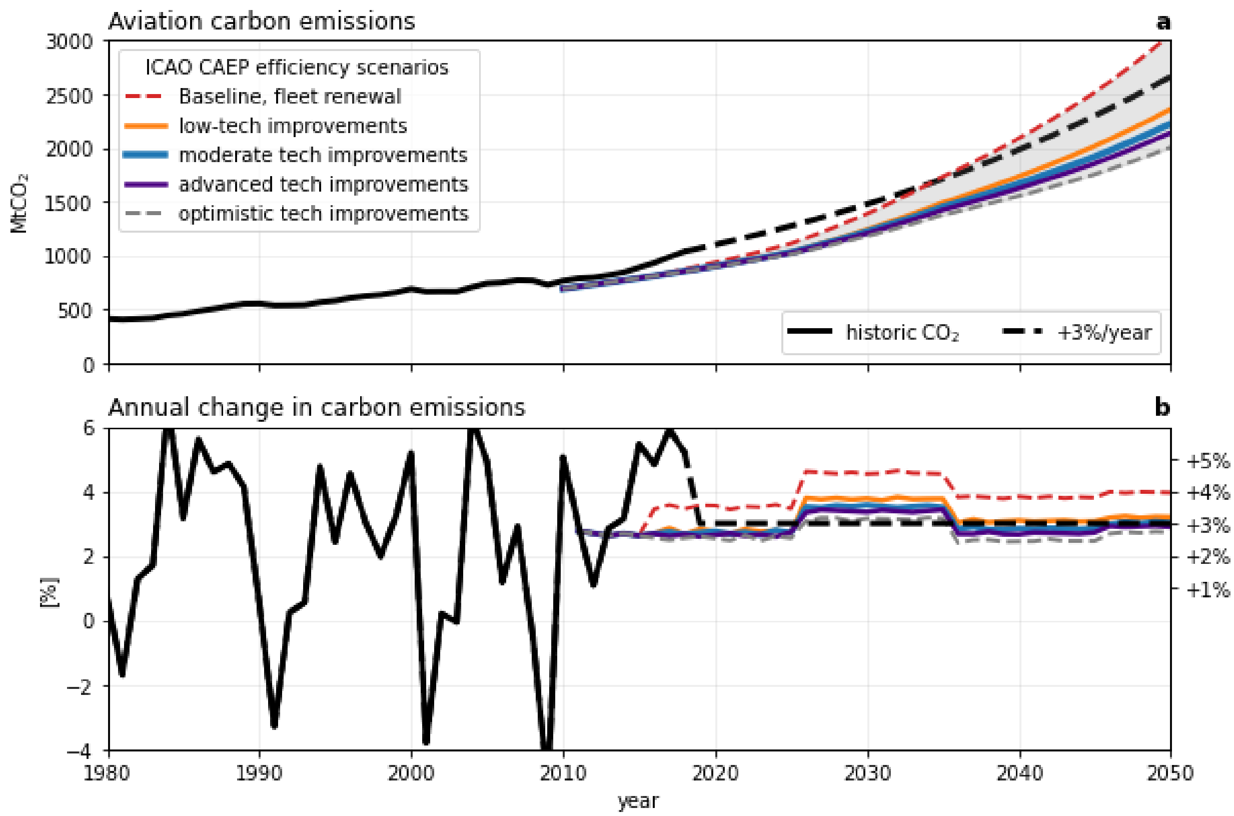

Figure S1. Annual increase in aviation CO_2 emissions for historic emissions and future projections. **a** Historical emissions (1970-2018) are taken from data of the International Energy Agency (IEA) as in Lee et al. (2020). The *No Pandemic* scenario here is taken from a mid-point growth scenario developed by the International Civil Aviation Organization (ICAO) which assumes moderate improvements in technology and operations (Fleming and de Lépinay 2019) and increases by about 3%/year. **b** Growth factors are utilized rather than the absolute data because of the well-known (~10-12%) mismatch between bottom-up idealized inventories and actual fuel usage recorded by the IEA (David S. Lee et al. 2009).

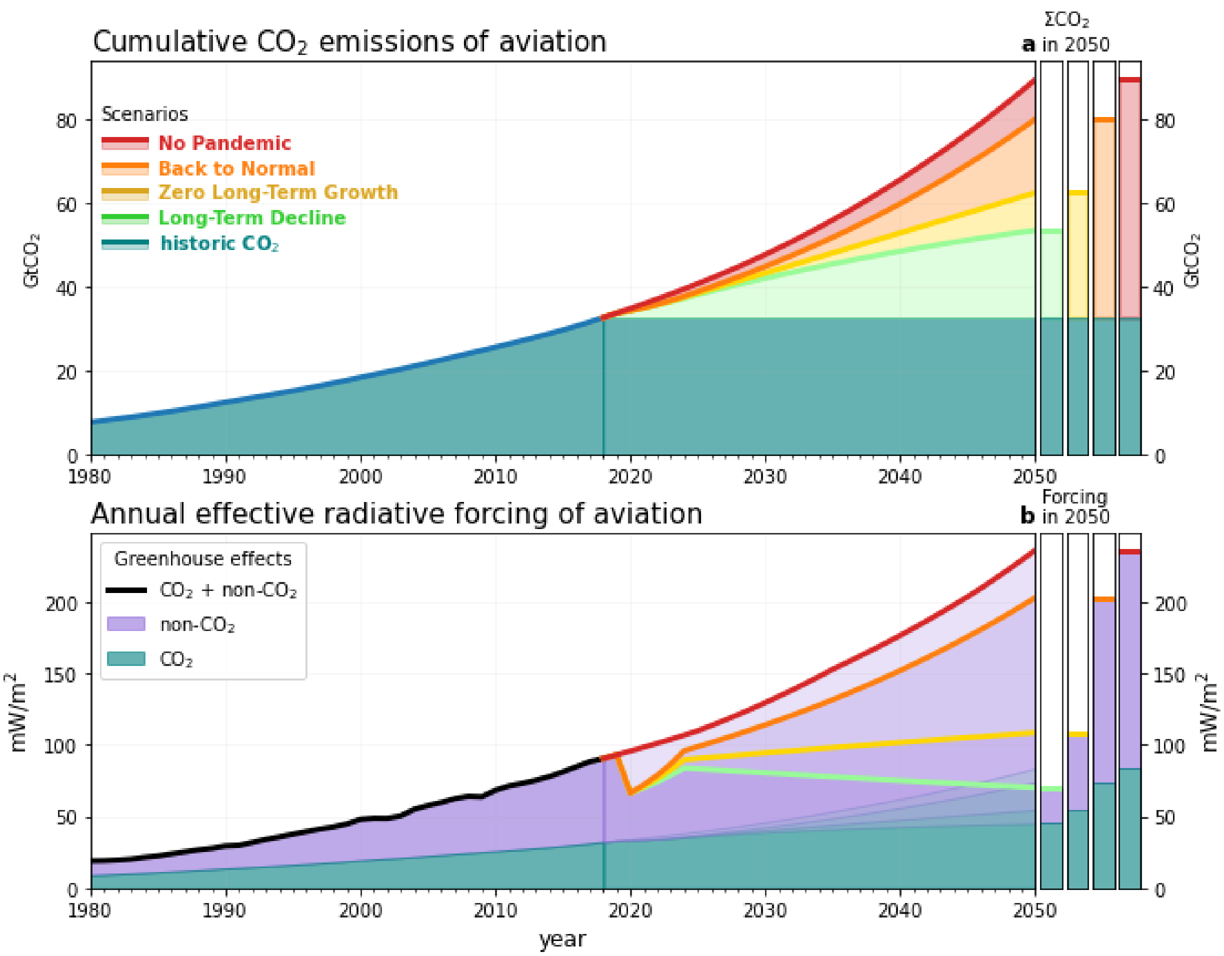

Figure S2. Non-CO_2 greenhouse effects dominate over CO_2 emission in the effective radiative forcing from aviation. **a** Aviation's cumulative CO_2 emissions from 1940 to 2018 for historic emissions and until 2050 following the four scenarios as in Fig. 1 (same colour-coding). **b** Annual effective radiative forcing resulting from CO_2 and non-CO_2 effects (see Fig. S3) until 2050 under the scenarios from **a**.

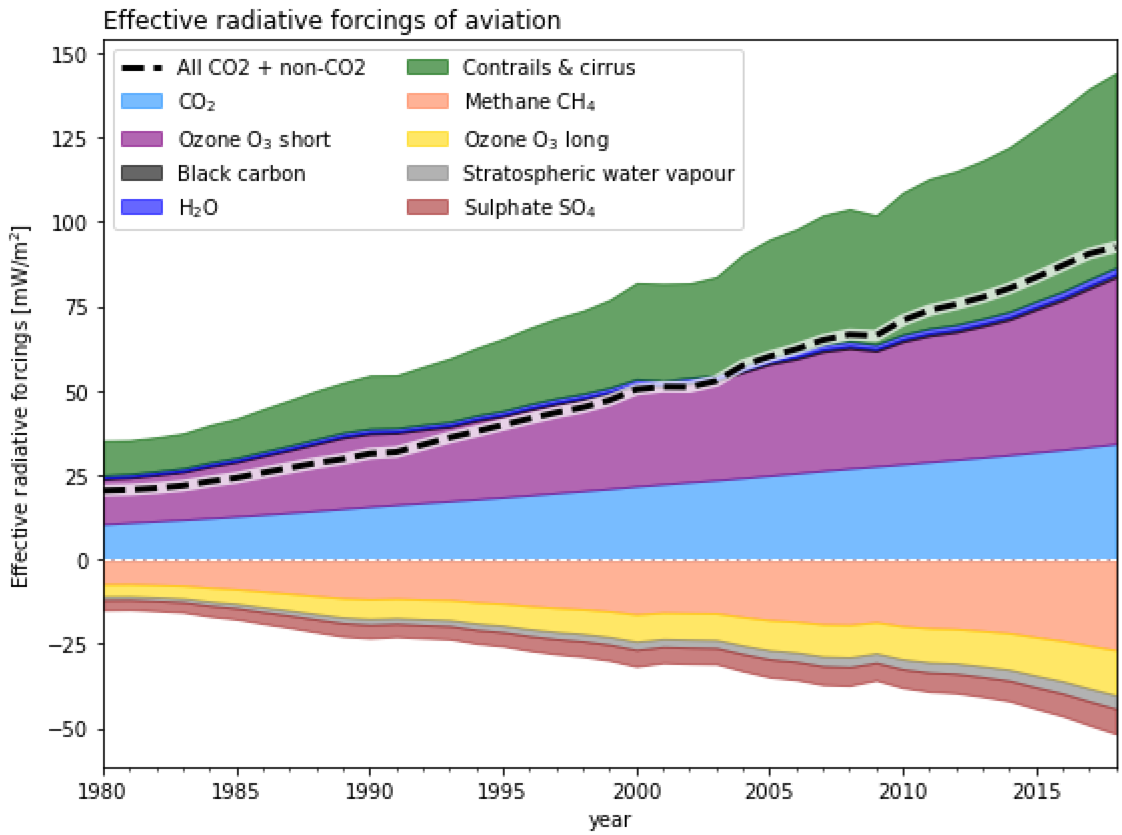

Figure S3. Contributions to CO_2 and non-CO_2 (all other) greenhouse effects from global aviation, based on historic fuel consumption and flight distances from 1980 to 2018. See Table S1 and Lee et al. (2020) for further information.