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Definitions and implications of climate-neutral aviation

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To meet ambitious climate targets, the aviation sector needs to neutralize CO_2 emissions and reduce non-CO_2 climatic effects. Despite being responsible for approximately two-thirds of aviation's impacts on the climate, most of aviation non-CO_2 species are currently excluded from climate mitigation efforts. Here we identify three plausible definitions of climate-neutral aviation that include non-CO_2 forcing and assess their implications considering future demand uncertainty, technological innovation and CO_2 removal. We demonstrate that simply neutralizing aviation's CO_2 emissions, if nothing is done to reduce non-CO_2 forcing, causes up to 0.4 °C additional warming, thus compromising the 1.5 °C target. We further show that substantial rates of CO_2 removal are needed to achieve climate-neutral aviation in scenarios with little mitigation, yet cleaner-flying technologies can drastically reduce them. Our work provides policymakers with consistent definitions of climate-neutral aviation and highlights the beneficial side effects of moving to aircraft types and fuels with lower indirect climate effects.

The aviation sector is expected to quickly recover from the COVID-19 pandemic and resume its trend of rapid growth[1–3]. Due to the complexity and uncertainty of aviation's non-CO_2 effects on the climate[4–6], on top of the general difficulty to regulate international aviation emissions[7,8], aviation's non-CO_2 effects are currently excluded from international climate agreements (that is, the Paris Agreement), other aviation mitigation policies (for example, efforts from the International Civil Aviation Organisation (ICAO) such as the Carbon Offsetting and Reduction Scheme for International aviation (CORSIA)[9] and its mid-century targets[8]) and carbon markets (for example, the European Emissions Trading System[4,7]). If aviation's non-CO_2 effects are left unmitigated, the sector's expansion could, however, conflict with climate goals such as those in the Paris Agreement[7,10–13].

The burning of jet fuel at high altitude affects the climate both directly—due to the emissions of CO_2, H_2O, sulfur dioxide and soot—and indirectly due to the short-lived formation of contrail cirrus and the changes in O_3, CH_4 and stratospheric water vapour due to NO_x emissions[14,15]. These various effects have different magnitudes and lifetimes and jointly have contributed about 4% of the anthropogenic forcing from pre-industrial times[14,16], two-thirds of which are due to non-CO_2 effects (with uncertainties between 38–77%) (ref. [14]). While the non-CO_2-related effects are both warming and cooling, their net effective radiative forcing—dominated by contrail cirrus—is positive[14,17,18].

Climate-neutrality targets are designed to guarantee that human activities, such as aviation, stop further contributing to climate change[19]. For a long-lived greenhouse gas such as CO_2, stabilizing atmospheric concentrations to avoid further warming requires reducing net emissions to zero[20–22]. This is not the case, however, for the short-lived effects caused by aviation[19,23]. Ceasing emissions would eliminate the (net positive) short-lived terms of radiative forcing, resulting in a cooling relative to the period preceding the cessation. Thus a definition of climate neutrality requires setting the baseline relative to which net emissions are neutral[19,24]. First attempts to investigate the implications of climate neutrality and the related issue of offsetting non-CO_2 forcing with CO_2 removal exist for some sectors dominated by short-lived greenhouse gases, such as agriculture[23,25,26]. There has been no such analysis of the aviation sector, which has far more complex climatic effects. We address this deficit here.

In this study, we explore the climate impacts of aviation under different Shared Socioeconomic Pathways (SSPs), that is, SSP1–2.6 and SSP5–8.5, encompassing a large range of possible future changes in demand, CO_2 intensity and energy efficiency. Besides scenarios where fossil jet fuels continue playing a predominant role (*Fossil jet fuels*), we additionally assess two technology scenarios envisioning a complete transition to zero-carbon fuels (*Zero-CO_2 fuels*) or hypothetical emissions-free aircraft (*No-emissions aircraft*). Finding that climate neutrality, and not carbon neutrality, is necessary to align the aviation sector with Paris-compatible climate change mitigation, we propose and formalize three plausible definitions of climate-neutral aviation that consider non-CO_2 effects. We calculate the levels of CO_2 removal required to offset the residual emissions overshooting the different climate neutrality targets. Finally, we assess the impacts of these climate neutrality frameworks, including the needed CO_2 removal, on global temperature in the context of the different demand and technology scenarios.

Our modelling approach is summarized in Fig. 1. We use empirical relationships to translate aviation emissions into climate forcing (the sensitivity parameters, σ, of each emitted aviation species and indirect effect[14]), an alternative application of the Global Warming Potential (the GWP*)[27–29] as a heuristic to estimate carbon-removal rates and a reduced-complexity climate model (the Finite Amplitude Impulse Response model, FaIR)[30,31] to compute temperature change. In doing so, we fully propagate the uncertainty (that is, the standard error of the sensitivity parameters and of zero-carbon fuels emissions reduction) through our modelling chain. More details are provided in Methods.

The role of non-CO_2 effects in future aviation scenarios

In Fig. 2, we show the evolution of the different terms of aviation's effective radiative forcing (ERF) according to the two socioeconomic and three technology pathways. While non-CO_2 effects

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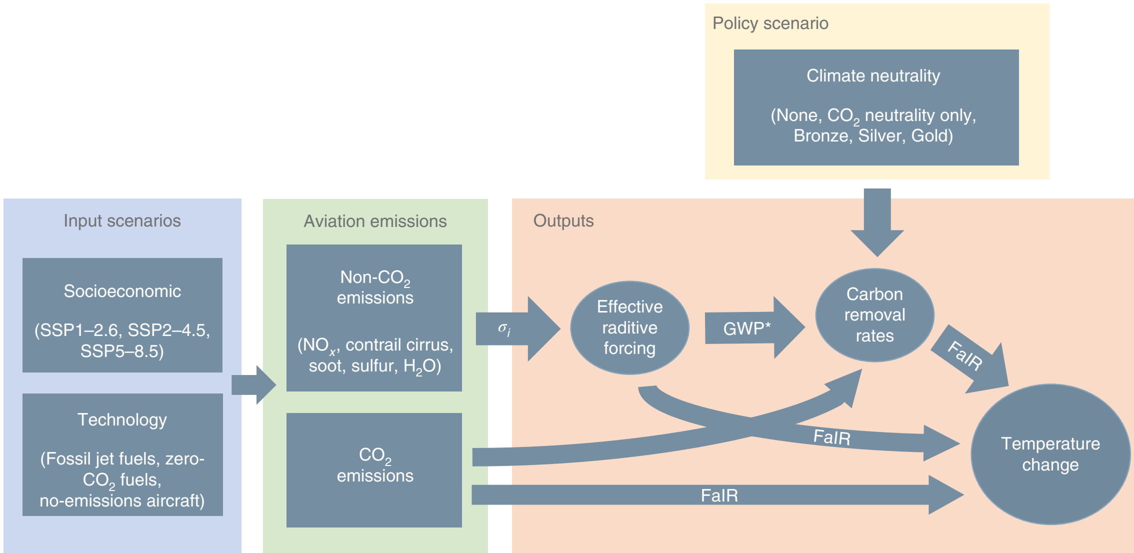

Fig. 1 | Modelling approach used in this study. First, we explore different scenarios of future aviation, taking into consideration future technologies and demand changes following different socioeconomic pathways. These scenarios result in different pathways of future aviation emissions and indirect effects (Supplementary Methods 1.1). Then, we use the sensitivity parameters, σ_i, to calculate the effective radiative forcing of the different aviation species and its uncertainty. We then apply different definitions of climate neutrality (Gold, Silver and Bronze) and calculate the needed carbon-removal rates, using the GWP* metric to establish a relationship between aviation non-CO_2 forcing and CO_2 removal. Finally, we input CO_2 emissions and removal rates and non-CO_2 effective radiative forcing in a reduced-complexity model (FaIR) to calculate the temperature outcomes of the different scenarios of climate neutrality.

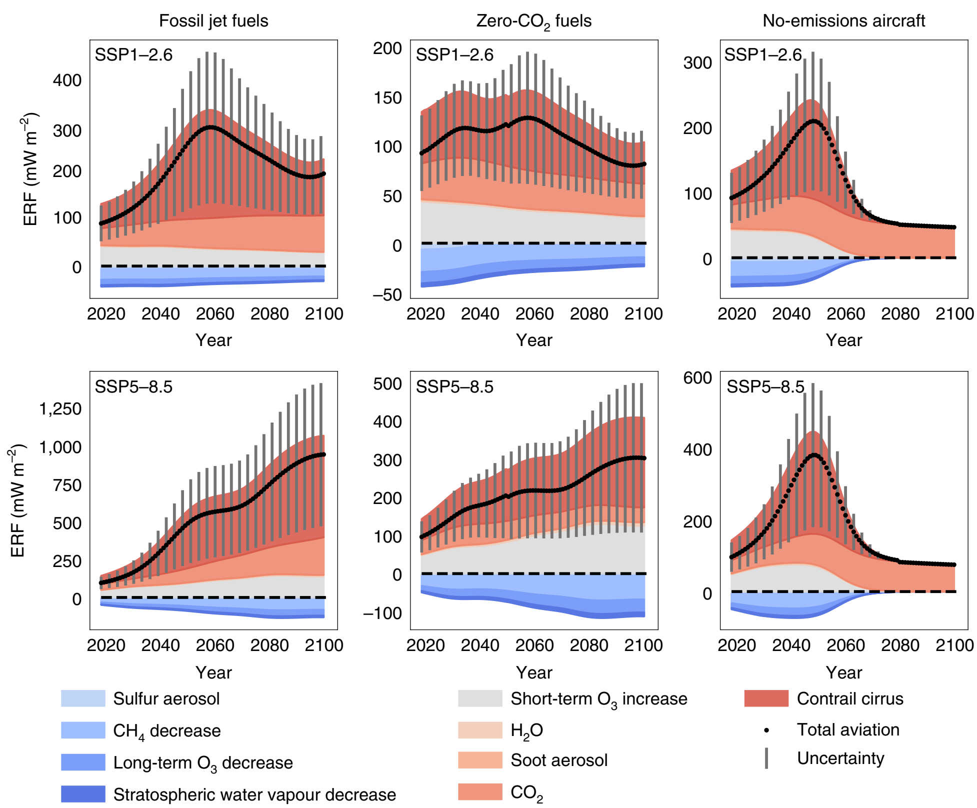

Fig. 2 | ERF components of aviation. Components with a negative ERF (cooling effect on the climate; blue shades): sulfur aerosol and decreases in CH_4, ozone and stratospheric water vapour due to NO_x emissions. Components with a positive ERF (warming effect on the climate; grey to red shades): H_2O, soot, CO_2 and contrail cirrus. The black dots show the total ERF in each year, while the grey bars encompass the standard deviation of the total ERF of aviation. Different panels relate to different input emission scenarios, with rows for the most optimistic (SSP1–2.6) and most pessimistic (SSP5–8.5) socioeconomic scenarios and columns for different technology scenarios. The black horizontal line corresponds to zero effective radiative forcing and shows the divide between warming and cooling species.

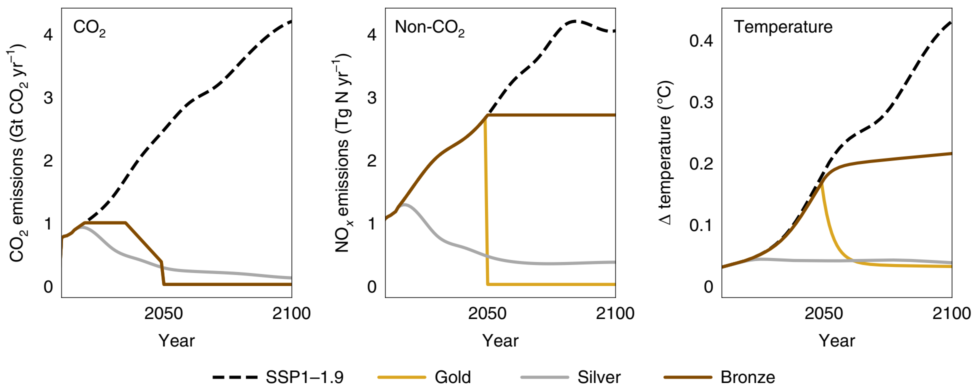

Fig. 3 | Schematics of the three plausible definitions of climate-neutral emissions identified in this study. Below the three definitions, we show the time series of CO_2 emissions (left), non-CO_2 emissions (using NO_x as explanatory example, centre) and the resulting temperature outcome of the different climate neutrality definitions (right). At the onset of climate neutrality, under the Gold definition, all aviation emissions reach net zero. Under the Silver definition, emissions follow SSP1–1.9. Under Bronze, CO_2 emissions are eliminated while non-CO_2 emissions are stabilized. Before 2050, emissions follow the ICAO's mid-century targets (Methods) in all but the Silver definition. The dashed line shows the emission and temperature trajectory in the SSP5–8.5 scenario (an intermediate socioeconomic scenario) for the case in which no climate neutrality framework is introduced.

currently account for 67% of aviation's total historical ERF (38–77% when considering the whole uncertainty range)[14], their future contribution could substantially change. The non-CO_2 term is largely dominated by the ERF of contrail cirrus, followed by the short-term O_3 increase caused by NO_x emissions. Under the *Fossil jet fuels* scenarios, CO_2 emissions are only partially mitigated (for example, via energy efficiency and CO_2 intensity reductions) and thus their ERF continues increasing. For contrail cirrus and other short-term forcing, the growth trajectory of emissions determines whether short-term forcing decreases in the second half of the century (as in SSP1–2.6) or continues increasing (as in SSP5–8.5). Under assumptions of undisturbed sectorial growth as in SSP5–8.5, the share of ERF due to CO_2 decreases from the observed 38% (27–67%) in 2018 to 26% (18–52%) in 2100, while the contribution of contrail cirrus rises from 58% (30–69%) to 71% (42–81%). In SSP1–2.6, the non-CO_2 ERF terms peak at 79% (53–86%) before 2060 and shrink to 61% (31–73%) by 2100 because of decreasing emissions.

A rapid transition to cleaner-flying technologies changes the breakdown of ERF by aviation species. For instance, the 100% transition to zero-carbon fuels by 2050 in the *Zero-CO_2 fuels* scenario eliminates CO_2 emissions, stabilizing the ERF of CO_2. As a result, the relative contribution of non-CO_2 effects to the total ERF increases, despite zero-carbon fuels partially mitigating some of these effects. Consequentially, by 2100 CO_2 contributes only 13% (8–36%) to the total aviation ERF under SSP5–8.5, while contrail cirrus contributes 78% (39–86%). While in this scenario, the short-term increase in O_3—an indirect effect of NO_x emissions—seems to play a prominent role, it is almost completely compensated by NO_x cooling effects.

In the exploratory *No-emissions aircraft* scenario, about a quarter of the flights are emissions free by 2050 and all of them by 2080, eliminating all short-term ERF contributions and lowering the total ERF by the end of the century. Only a rapid shift to no-emissions aviation would thus justify the current standard of excluding non-CO_2 effects from mitigation efforts[7–9,32]. Yet such a transition relies on very optimistic assumptions about technology development and diffusion that might well not materialize. For this reason, aviation's non-CO_2 forcing should be addressed through climate neutrality targets.

Definitions of climate neutrality

We identify three plausible baselines and formalize three corresponding definitions of climate-neutral aviation (Fig. 3). Our definitions include the complexities arising from the short-lived effects of aviation, particularly the fact that climate-neutral aviation does not require all aviation emissions to reach net zero to stabilize ERF[19,33]. Instead, climate-neutral aviation depends on the specific ERF baseline relative to which the climate is stabilized.

The most ambitious and stringent baseline, which we label *Gold*, considers aviation to be climate neutral compared with a world without aviation emissions. After the onset date of climate neutrality (2050), all aviation climate effects must be down to net zero. The complete elimination of short-lived aviation species from the atmosphere, such as short-lived greenhouse gases and aerosols, leads to the neutralization of short-term indirect effects, too, thus reducing forcing and ultimately temperatures relative to 2050 levels.

The second baseline, which we label *Silver*, considers the climate to be neutral relative to a world on a 1.5 °C trajectory, which is achieved by limiting aviation forcing to that in the SSP1–1.9 scenario. This causes about 0.04 °C warming by 2100, which we refer to as the 1.5 °C-compatible contribution of aviation.

The third baseline, which we label *Bronze*, considers aviation to be climate neutral compared with its contribution at the onset date of climate neutrality (2050) by stabilizing aviation forcing after 2050 owing to a balance between sources and sinks of aviation emissions. To do so, all long-lived emissions need to be net zero, while short-lived forcing must stabilize at the levels reached at the onset date of climate neutrality, allowing for offsets between the two.

Impacts of different definitions of climate neutrality

To assess the Gold, Silver and Bronze definitions of climate neutrality, we model their CO_2 removal requirements and absolute temperature changes using empirical sensitivity parameters, the GWP* metric and a reduced-complexity climate model, FaIR (as detailed in Fig. 1 and Methods). Without further efforts to mitigate emissions, the projected growth in aviation causes 0.10 ± 0.05 °C of warming under SSP1–2.6 and 0.44 ± 0.22 °C of warming under SSP5–8.5 in 2100, as shown in Fig. 4 for the *Fossil jet fuels* scenario. This temperature increase is roughly one order of magnitude larger than the 0.04 °C temperature increase from aviation in the 1.5 °C-compatible SSP1–1.9 scenario (Fig. 4, '1.5 °C compatible' dashed line). Given that global mean temperature has consistently been more than 1 °C warmer than the pre-industrial mean since 2014, these additional temperature increases alone would lock in about 1.5 °C global warming.

Setting a carbon neutrality target—that is, offsetting via CO_2 removal all aviation CO_2 emissions that remain after demand reductions and technological improvements—mitigates up to only 20% (14–41%) of the warming due to the aviation sector.

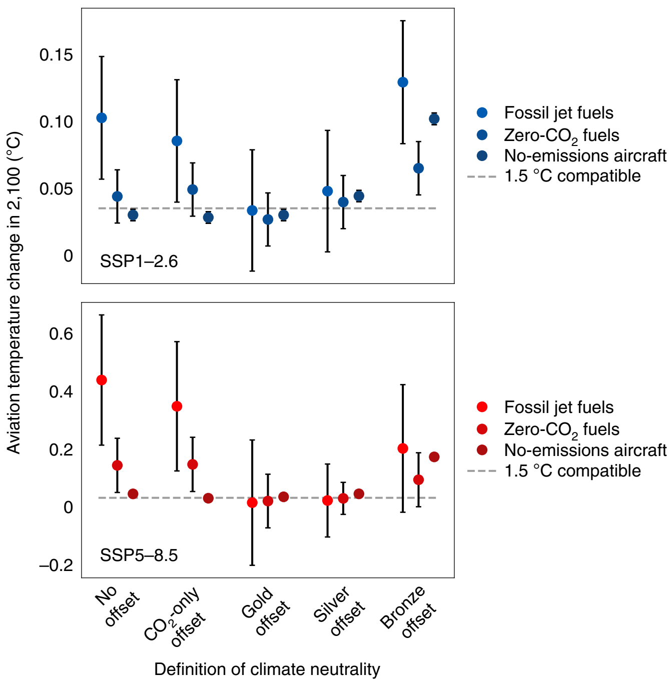

Fig. 4 | Changes in temperature by the year 2100 due to aviation emissions only under two different socioeconomic pathways. The points show temperature changes achieved under different technology pathways (fossil jet fuels, zero-carbon fuels and no-emissions aircraft) and definitions of climate neutrality (Gold, Silver and Bronze) under SSP1–2.6 (top) and SSP5–8.5 (bottom). The dashed line ('1.5 °C compatible') shows the absolute temperature change caused by aviation in a scenario compatible with the 1.5 °C target, SSP1–1.9. Error bars show the uncertainty range (Methods).

If demand continues growing, under the *Fossil jet fuels* scenario, non-CO_2 climatic impacts grow as well and jeopardize the mitigation efforts of carbon neutrality. By contrast, rapidly adopting novel technologies can substantially reduce aviation's contribution to global warming by reducing CO_2 and non-CO_2 effects without any CO_2 removal. *Zero-CO_2 fuels*, which burn more cleanly and thus emit less non-CO_2 species, lead to a smaller overshoot of the 1.5 °C-compatible temperature with 0.05 ± 0.02 to 0.15 ± 0.09 °C of warming by 2100. *No-emissions aircraft*, which eliminates all climatic impacts of aviation, drives temperatures down to levels almost compatible with the Paris Agreement across all demand scenarios (0.03 ± 0.00 °C to 0.05 ± 0.01 °C of warming by 2100). The degree of mitigation achieved by cleaner technologies is, however, sensitive to how fast these technologies overtake fossil fuelled aircraft types, although a change by ten years in the duration of the transition results in a maximum 17% change in temperature outcomes (Supplementary Table 2).

While technology can theoretically reconcile aviation-demand growth and climate change mitigation, such reconciliation rests upon very ambitious and potentially unfeasible technological breakthroughs and optimistic assumptions on their ability to rapidly curb emissions (for example, full zero-carbon fuels substitution by 2050 and zero-emissions airplanes substitution by 2080 or zero life-cycle emissions). The reliance on demand reductions and technological transitions to meet mitigation goals can be reduced by deploying CO_2 removal to neutralize all residual emissions and indirect effects[34–36]. Yet we find that different definitions of climate neutrality yield different CO_2 removal requirements and temperature outcomes. Overall, the Gold and Silver definitions robustly achieve temperatures compatible with the 1.5 °C goal while Bronze locks in additional warming. Silver succeeds by definition because it deploys CO_2 removal to offset all deviations of aviation's emissions from the 1.5 °C-compatible trajectory. Small deviations from the target temperature are due to the conversion of non-CO_2 emissions in CO_2 removal (Supplementary Methods 1.4). Gold, on the other hand, is designed to neutralize aviation's historic non-CO_2 effects after the onset date (2050), leading to warming contributions between 0.02 ± 0.2 and 0.03 ± 0.04 °C in 2100. Bronze climate neutrality fails to comply with the Paris temperature goals, highlighting that net-zero CO_2 in combination with constant non-CO_2 from aviation is insufficient. Even a rapid transition to emissions-free airplanes leads to overshoots of the Paris-compatible temperature goal because its effects manifest only in the second half of the century. Moreover, under the peak and decline SSP1–2.6 scenario, we observe the paradoxical situation that Bronze (which stabilizes forcing at 2050 levels) increases 2100 temperatures compared with no climate policy. The hypothetical *No-emissions aircraft* scenario thus well illustrates the risks of introducing climate neutrality targets (such as Bronze) that are not robust to future disruptive technological transitions.

We further show the temporal evolution of temperatures under different climate-neutrality frameworks (Fig. 5). In all but the Silver framework, which assumes early action, we observe substantial overshoots of the 1.5 °C-compatible trajectory because CO_2 removal is deployed only from 2050 to meet climate neutrality. While Bronze nearly stabilizes temperatures at their 2050 levels, Gold quickly drives temperatures down in the second half of the century, leading to 2100 temperatures such as those in Silver. Both Gold and Silver also cause temporary drops in temperature below the 1.5 °C trajectory, related to oversteering of CO_2 removal rates. Even though the temperature changes are substantially smaller in the *Zero-CO_2 fuels* scenario, their dynamics are similar to those in the *Fossil jet fuels* scenarios. Under *No-emissions aircraft*, all scenarios but Bronze converge at the same temperature in 2100, including those without a climate neutrality framework. Yet only Silver can prevent important temporary overshoots of the 1.5 °C-compatible trajectory. Finally, the eradication of indirect climatic effects due to emissions-free aircraft reduces the temperature uncertainties to negligible amounts in 2100 because the positive contributions before mid-century cancel the negative ones thereafter.

The Gold, Silver and Bronze definitions use CO_2 removal to varying degrees (Fig. 6). Without technological changes (*Fossil jet fuels* scenario), the mean rates of CO_2 removal are very large and comparable to total CO_2 removal rates aggregated over all sectors in Paris-compatible scenarios, shedding doubt on their feasibility[37]. Rates are highest under the Gold climate neutrality, reaching on average 12 ± 8 Gt CO_2 per year between 2020 and 2100 in the SSP5–8.5 scenario (with yearly rates over 20 Gt CO_2 per year by mid-century; Supplementary Fig. 6). Silver also uses carbon removal extensively, yet average rates remain at or below 10 Gt CO_2 per year. Bronze comes with the lowest rates of CO_2 removal. These even become negative—corresponding to additional CO_2 allowances—in the low-demand SSP1–2.6 or *No-emissions aircraft* scenarios but also do not ensure compatibility with the Paris temperature goals.

Switching to cleaner-flying technologies allows to achieve climate neutrality targets with substantially less CO_2 removal. While for most cases switching to zero-carbon fuels enables climate neutrality with 70–89% less CO_2 removal, switching to no-emissions airplanes drives mean rates of CO_2 removal to or below zero across all scenarios and definitions of climate neutrality. The switch to no-emissions airplanes undoes the short-lived forcing and thereby enlarges aviation's carbon budget, leading to negative CO_2 removal (that is, GWP*-based CO_2-equivalent emission allowances, the grey bars in the *No-emissions aircraft* scenario, Fig. 6). Similarly, negative values of CO_2 removal occur in SSP1–2.6 due to demand reductions and subsequent decline in non-CO_2 forcing.

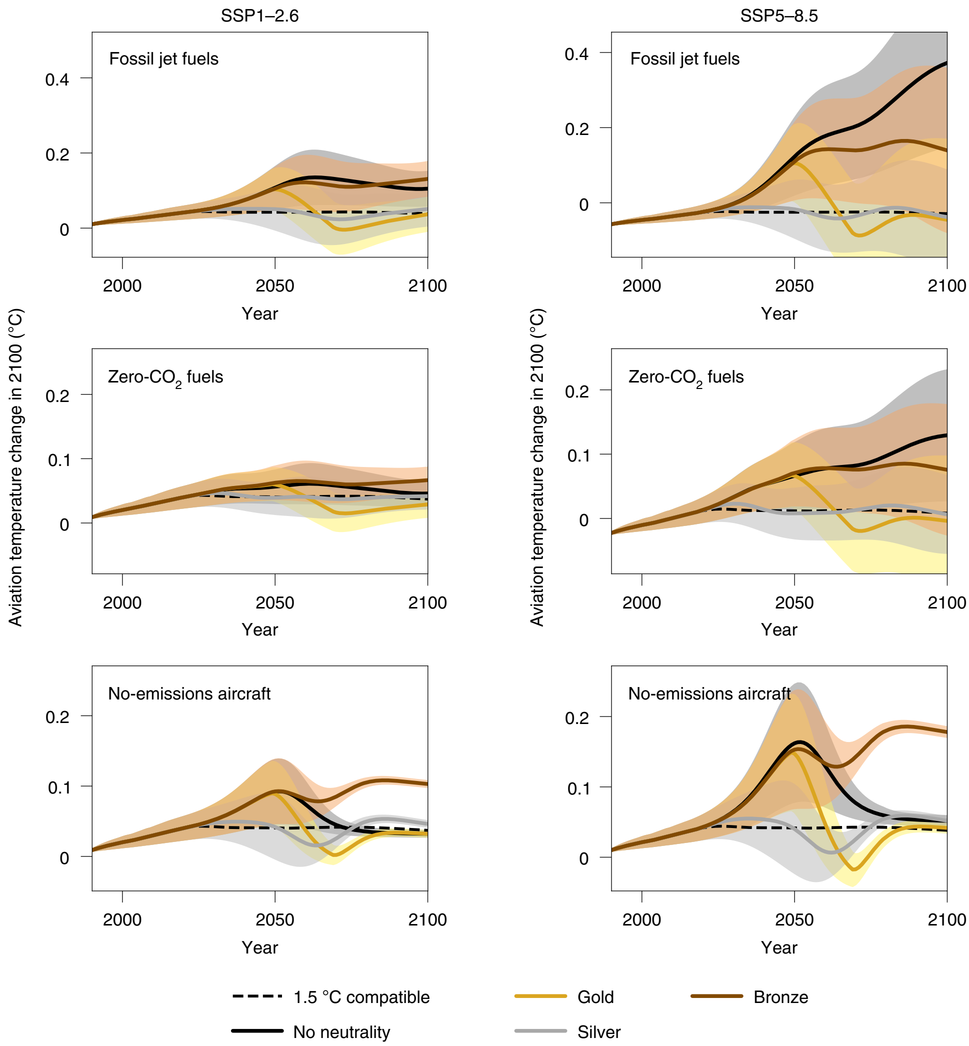

Fig. 5 | Changes in temperature throughout the twenty-first century under different socioeconomic pathways and technologies. Left: SSP1–2.6. Right: SSP5–8.5. Differently coloured lines represent different definitions of climate neutrality. Shaded areas show the uncertainty range (Methods). The dashed line ('1.5 °C compatible') shows the absolute temperature change caused by aviation in a scenario compatible with the 1.5 °C target, SSP1–1.9.

Gold and Silver require similar cumulative CO_2 removal, reaching up to 950 ± 640 Gt CO_2 under the highest aviation-demand scenario. While Silver CO_2 removal rates exceed 1 Gt CO_2 per year already in 2022, Gold does so only in 2032. The same cumulative removals thus spread out over a longer period of sustained CO_2 removal deployment in Silver. Bronze has substantially lower volumes of CO_2 removed, and the most negative CO_2 removal because it deploys negative CO_2 removal to stabilize temperatures at their 2050 levels even when temperature declines after 2050, as in the SSP1–2.6 and *No-emissions aircraft* scenarios.

Discussion and conclusions

Our work shows the issue with current mitigation policies ignoring the non-CO_2 effects of aviation and provides consistent definitions of climate-neutral aviation that could be used in future climate policy. Additionally, it highlights the beneficial side effects of switching to energy carriers—zero-carbon fuels, hydrogen or electricity—with lower indirect climatic effects.

We show that tackling only aviation's CO_2 emissions neglects up to 90% of future aviation's contribution to climate change. We moreover demonstrate that climate neutrality, and not carbon neutrality, is needed to achieve the Paris Agreement's long-term temperature goals because carbon neutrality causes between 0.09 ± 0.05 °C to 0.35 ± 0.22 °C of additional warming from aviation alone (in SSP1–2.6 and SSP5–8.5, respectively). These results are in line with the literature finding temperature changes of 0.2–0.35 °C by 2100 under emission scenarios between SSP1–2.6 and SSP5–8.5 (refs. [11,38]). They are moreover largely compatible with studies taking into account the effects of COVID-19 and finding about 0.1 °C of warming by 2050 if no substantial efforts to mitigate the aviation sector are undertaken[11,16].

We show that the precise definition of climate neutrality matters; definitions diverge strongly in their temperature outcomes. The Bronze definition, which stabilizes aviation's climatic effects from 2050 onwards, overshoots the Paris temperature targets in 2100 by up to 0.17 ± 0.22 °C and should be used only in combination with Paris-compatible mid-term mitigation targets. By contrast, the other two definitions lead to Paris-compatible temperatures in 2100 by allowing the aviation sector to continue polluting following the SSP1–1.9 trajectory (Silver) or imposing net-zero aviation forcing in the second half of the century (Gold). However, only the Silver framework avoids substantial temporary overshoots of the 1.5 °C-compatible temperature trajectory.

Given the very high, and probably unfeasible[37,39], rates of CO_2 removal needed to reconcile demand growth with Paris-compatible climate mitigation using current technology (exceeding 10 Gt CO_2 per year sustained over many decades for aviation alone), either a

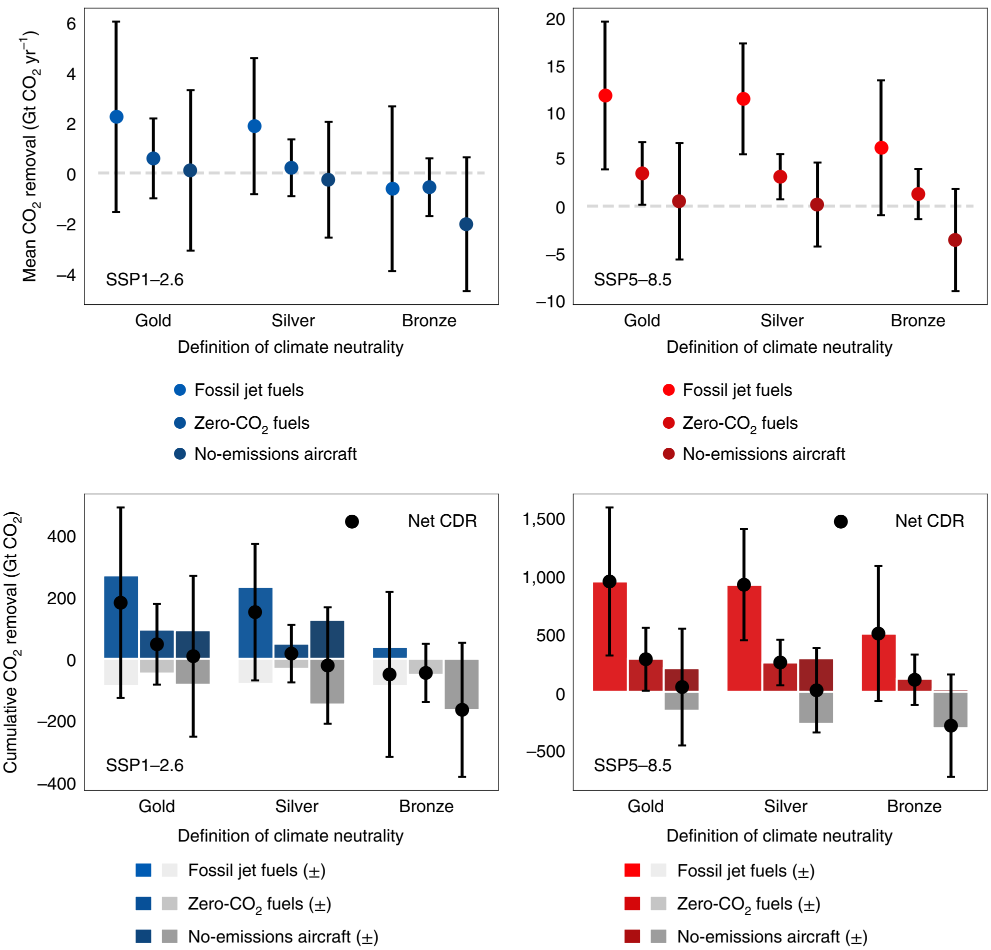

Fig. 6 | CO_2 removal rates and volumes contained in the different definitions of climate neutrality for SSP1–2.6 and SSP5–8.5 and different technology scenarios. Top: mean CO_2 removal rates (point plots). Bottom: cumulative CO_2 removal volumes (bar plots). CO_2 removal volumes are divided between positive (coloured bars) and negative (grey bars), with points indicating the net cumulative CO_2 removal ('Net CDR'). Negative CO_2 removal corresponds to the amount of CO_2 that can be emitted in addition to what is already contained in the corresponding emissions scenario and can thus be interpreted as additional CO_2 allowances to be allocated to other sectors. Error bars show the standard deviations.

limit on aviation growth or a transition to cleaner-flying technologies is necessary to achieve climate-neutral aviation. Switching to zero-carbon fuels would reduce CO_2 removal requirements by up to 88% while switching *early* to zero-emissions aircraft would completely avoid the need for CO_2 removal. Whereas zero-carbon fuels are experiencing rapid technological advances, despite still facing many economic challenges, zero-emissions airplanes that could replace current commercial aircraft are currently highly speculative due to constraints such as battery weight.

In addition to potentially prohibitive CO_2 removal in some of the scenarios, there are implementation challenges when operationalizing the suggested neutrality definitions[40]. Surprisingly, the costs for CO_2 removal appear affordable: assuming CO_2-removal costs of approximately US\$250 ± US\$100 ton^{-1} (refs. [39,41]), an exemplary flight from Zurich to New York would become, on average, up to US\$76 ± US\$99 more expensive per passenger under the Gold climate neutrality definition (US\$97 ± US\$85 for Silver and US\$37 ± US\$79 for Bronze). Adopting zero-carbon fuels or no-emissions airplanes would cut the costs related to CO_2 removal by up to 72% (67–293%) and 73% (54–75%) respectively, thereby effectively paying a dividend of technology development. Yet additional costs would arise from a rapid transition to cleaner-flying technologies, potentially affecting sectorial growth, emissions and thus the volumes of CO_2 removal required to comply with climate neutrality. Distributing these costs fairly to individual flights would moreover be challenging because the marginal climatic effect of a flight depends on the total flight volume.

Overall, we have demonstrated how climate-neutral aviation can be consistently defined, taking CO_2 and non-CO_2 effects into account. Reaching climate-neutral aviation requires technological change or demand reductions as offsetting all climatic effects of aviation is infeasible if humankind continues to fly with conventional jet fuels while following anticipated demand growth.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-022-01404-7.

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Methods

In this study, we investigate climate-neutral aviation by jointly capturing the CO_2 and non-CO_2 effects of aviation and combining them with scenarios of demand and technological change.

Demand and technology scenarios. To examine the role of sectorial growth, CO_2 efficiency and energy intensity, we use aviation emissions under three socioeconomic pathways, namely SSP1–2.6, SSP2–4.5 and SSP5–8.5 (refs. [42,43]). While results for the intermediate SSP2–4.5 scenario are shown in Supplementary Figs. 1, 2, 3 and 7, here we show results only for the SSP1–2.6 and SSP5–8.5 scenarios, which encompass a broad range of possible futures, from a broadly sustainable pathway (SSP1) to a fossil fuel-driven development (SSP5). Compared with the 1.5 °C-compatible SSP1–1.9 scenario, they all feature demand growth causing a temperature overshoot that makes the introduction of additional policies and targets necessary. Assuming that the underlying socioeconomic parameters remain constant, we additionally assess three different technology scenarios to examine the role of technological change (Supplementary Methods 1.1).

First, the *Fossil jet fuels* scenario follows the emission pathways contained in the SSP scenarios and assumes the continued deployment of fossil jet fuels, although emissions mitigation happens to a certain degree and in form of operational and fuel efficiency improvements. Emissions for this scenario are depicted in Supplementary Fig. 1.

Second, the *Zero-CO_2 fuels* scenario assumes a rapid S-shaped takeover of sustainable fuels that begins in 2020 and leads to 100% carbon-free aviation by 2050. Under this scenario, we consider a mix of future alternative jet fuels that manage to eliminate CO_2 emissions from advanced biofuels to power-to-liquid jet fuels. Due to the higher costs of zero-carbon fuels compared with fossil jet fuels, such a rapid diffusion would only be possible if technology development and scale-up are guided by specific policy efforts[44–47]. Zero-carbon fuels can ensure net-zero aviation CO_2 emissions if they are produced in a carbon-negative way (for example, using direct air-captured CO_2 (ref. [48])) because of a balance between emissions during combustion and removal during fuel production.

Here we assume that the emissions reductions of zero-carbon fuels correspond to those due to a 100% shift to Fischer–Tropsch synthetic fuels produced from air-captured CO_2. Zero-carbon fuels differ from fossil jet fuels in their chemical composition and thus their emissions[49,50], which we evaluate by linearly scaling the empirically observed emission changes of soot, sulfur dioxide and hydrogen due to a blend of 41% Fischer–Tropsch synthetic fuel[50] (Supplementary Table 2). Changes in emissions of particulate matter (prominently, soot) also affect contrail cirrus formation[50]. Reducing soot emissions leads to a nonlinear, non-monotonic change in the formation of ice nuclei that is sensitive to background temperature conditions[17]. This change causes nonlinear responses in contrail cirrus' radiative forcing[18], which in our modelling, linearly responds to changes in contrail cirrus length. Using the relationships between these factors identified by previous simulation exercises[17,18], we estimate the reduction in contrail cirrus caused by the scaled reduction in soot (Supplementary Methods 1.1). Finally, we elicit from different studies[49,51,52] that zero-carbon fuels slightly reduce NO_x emissions and set a best estimate and uncertainty encompassing the span of the literature. We exclude life-cycle emissions of zero-carbon fuels assuming that in a world committed to climate neutrality and aligned with the Paris Agreement, these are negligible and already neutralized as part of industrial and energy mitigation efforts.

Third, the *No-emissions aircraft* scenario explores the impacts of hypothetical technological breakthroughs enabling emissions-free aviation. These could be, for example, advances in green hydrogen fuel cells or in electric aviation technologies[35,53,54]. Because of the power density of today's batteries and fuel cell stacks, 100% emissions-free aviation is currently unfeasible and unforeseeable in the near-term for mid- to long-haul flights[35,36]. However, a four-factor increase in cell specific energy would be sufficient to enable flights of around 1,000 km (ref. [36]). While insufficient to enable trans-oceanic flights, in the far future (post-2050), this problem could be overcome by technological innovations or by changes in operation (for example, oceanic airplane hubs to quickly swap batteries). Here we assume zero-emissions airplanes enter the market in 2030, replace around 25% of flights by 2050 (mostly short-haul flights) and take over the entire fleet by 2080. This 50-year diffusion curve is over the average of many clean technology transitions and exceeds the average lifetime of fleets (30 years) (ref. [55]). These technologies have the potential for near-zero equivalent CO_2 emissions if the grid successfully transitions to renewable energy and if the hydrogen is not of fossil fuel origin[36]. We assume that this technology eliminates all emissions, leading to a 100% reduction in indirect climatic effects, too. As for zero-carbon fuels, we assume that batteries, cell fuels and new aircraft are produced within the context of a world aligned with ambitious climate goals and thus that only renewable energy sources are involved in their production, leading to zero life-cycle emissions. Additional information on how the scenarios are constructed can be found in Supplementary Methods 1.1.

Offsetting aviation's climatic effects via CO_2 removal. In Fig. 1, we depict our approach to calculate the CO_2 removals needed to comply with a given definition of climate neutrality. Here we present the approach in greater detail. To model CO_2 removal rates and the climatic outcomes of different definitions of climate neutrality, we calculate ERF ($W\,m^{-2}$) in each scenario of aviation emissions following the approach described by Lee et al.[14]. To calculate the ERF of CO_2, we input historical and future aviation CO_2 emissions in the Finite Amplitude Response Model (FaIR) which simulates the global carbon cycle and calculates ERF resulting from CO_2 concentrations. For other terms of aviation's radiative forcing, such as contrail cirrus, NO_x and others, we use the sensitivity to emissions, σ_i (or in the case of contrail cirrus, the sensitivity to contrail cirrus length) reported in Lee et al.[1] (Supplementary Table 3). We calculate the ERF from the yearly (t) emissions E_i of each species i (or, for contrail cirrus, from their estimated length), as shown in equation (1) and propagate the standard deviation of σ_i (Supplementary Methods 1.2).

$$\mathrm{ERF}_i\,(t) = E_i\,(t) \times \sigma_i \tag{1}$$

We then define the ERF baseline to achieve under each climate neutrality definition, called $\mathrm{ERF}_{\mathrm{target}}$. First, Bronze corresponds to a stabilization of ERF from a start year t_{neutral}, implying that aviation must be net neutral with respect to its ERF from that year onwards. Second, Silver follows the aviation ERF from the SSP1–1.9 scenario that is in line with the 1.5 °C temperature target, allowing aviation to contribute to ERF increases as assumed in the Paris-compatible scenario but not more. Third, Gold corresponds to complete eradication of aviation emissions in the year t_{neutral}, which stabilizes the ERF from CO_2 emissions and eliminates the ERF from short-lived species. We formalize the approach by defining $\mathrm{ERF}_{\mathrm{target}}$ as

$$\mathrm{ERF}_{\mathrm{target}}\,(t) = \begin{cases} \mathrm{ERF}_{\mathrm{CO_2}\,(t_{\mathrm{neutral}})} + \sum_i \mathrm{ERF}_i\,(t_{\mathrm{neutral}}) & \text{Bronze} \\ \mathrm{ERF}_{\mathrm{CO_2},SSP1-1.9}(t) + \sum_i \mathrm{ERF}_{i,\,\mathrm{SSP1-1.9}}\,(t) & \text{Silver} \quad \text{if } t \geq t_{\mathrm{neutral}} \\ \mathrm{ERF}_{\mathrm{CO_2}\,(t_{\mathrm{neutral}})} - \mathrm{ERF}_{\mathrm{CO_2},\,natural}(t) & \text{Gold} \end{cases}$$

Before the onset year of climate neutrality (t_{neutral}), we deploy CO_2 removal to meet intermediate climate mitigation goals. These are the ICAO's goals of stabilizing CO_2 emissions to their 2019 levels up until 2035 (CORSIA) and of reducing them to the half of their 2005 levels by 2050[8,9]. For Silver, these intermediate targets are not relevant since $\mathrm{ERF}_{\mathrm{target}}\,(t)$ follows the 1.5 °C-compatible pathway from 2020 onwards.

We then set the sum of the ERF of all aviation species and from CO_2 removal ($\mathrm{ERF}_{\mathrm{CDR}}\,(t)$) to equal the target ERF:

$$\mathrm{ERF}_{\mathrm{CO_2}}\,(t) + \sum_i \mathrm{ERF}_i\,(t) + \mathrm{ERF}_{\mathrm{CDR}}\,(t) = \mathrm{ERF}_{\mathrm{target}}\,(t) \tag{2}$$

Where the amount of ERF that needs to be offset via CO_2 removal is denoted as $\mathrm{ERF}_{\mathrm{CDR}}\,(t)$. Theoretically, the rates of CO_2 removal can be explicitly calculated from $\mathrm{ERF}_{\mathrm{CDR}}\,(t)$, for example, following the approach by Jenkins et al.[56] or Brazzola et al.[25]. Yet this sort of computation is time and skills intensive and thus not in line with current practices under international treaties (for example, the United Nations Framework Convention on Climate Change, UNFCCC). Under a climate neutrality framework, airlines and governments need to resort to simple heuristics to calculate the necessary offsets to their residual emissions. To translate non-CO_2 ERF changes into CO_2 removal rates, we therefore use a conversion metric that captures the decay of short-lived species: GWP*. Although we acknowledge that this metric, too, has flaws (Supplementary Methods 1.3)[57,58], GWP* generally better represents the dynamics of short-lived forcing compared with constant CO_2 multipliers such as GWP100 or the emission weighting factor, EWF[27–29,59]. As shown in Supplementary Fig. 4, GWP* is more robust to changes in demand and technology, making it most suitable to calculate an equivalence between non-CO_2 ERF and CO_2 removals. Following the definition of GWP*, we calculate the CO_2-equivalent emissions of each non-CO_2 species ($E_{\mathrm{CO_2e*},i}$) overshooting the climate neutrality target as follows:

$$E_{\mathrm{CO_2e*},i} = \frac{-\Delta\left(\sum_i \mathrm{ERF}_{i,\mathrm{target}} - \sum_i \mathrm{ERF}_i\right)(t)}{\Delta t} \times \frac{H}{\mathrm{AGWP}_{H(\mathrm{CO_2})}} \tag{3}$$

where Δt equals 20 years, the time horizon H equals 100 years and the corresponding absolute global warming potential of CO_2 $\mathrm{AGWP}_{H(\mathrm{CO_2})}$ equals $8.8\times10^{-2}\,\mathrm{mW\,m^{-2}\,Mt^{-1}}$ as in Lee et al.[14]. The term in brackets denotes the difference between the current year and 20 years earlier:

$$\begin{aligned} \Delta\left(\sum_i \mathrm{ERF}_{i,\mathrm{target}} - \sum_i \mathrm{ERF}_i\right)(t) &= \left(\sum_i \mathrm{ERF}_{i,\mathrm{target}}\,(t) - \sum_i \mathrm{ERF}_i\,(t)\right) \\ &\quad - \left(\sum_i \mathrm{ERF}_{i,\mathrm{target}}\,(t-\Delta t) - \sum_i \mathrm{ERF}_i\,(t-\Delta t)\right) \end{aligned}$$

We then set the CO_2 removal rates equal to the yearly total CO_2-equivalent* emissions $\left(\sum_i E_{\mathrm{CO_2e*},i}\right)$.

To calculate the temperature change due to aviation under different climate neutrality emissions, we input CO_2 emissions, CO_2 removals and ERFs from non-CO_2 species in the FaIR model[30,31]. FaIR is an open-source reduced-complexity carbon cycle, atmospheric composition and climate model that calculates ERF and temperatures from input climate-forcing species concentrations or emissions. Because it does not explicitly spatially and temporally resolve atmospheric processes associated with aviation, such as contrail cirrus formation, we run the model in CO_2-only mode and externally provide non-CO_2 ERF contributions (calculated as per equation (1)). By contrast, the ERF resulting from the alterations of the carbon cycle due to CO_2 emissions and removals is explicitly modelled. The model calculates the temperature changes due to aviation from the ERF of CO_2 emissions, removals and non-CO_2 species based on a two-time constant model (equation (22) in Smith et al.[30]). We propagate the uncertainty in the ERF terms, resulting from the standard deviation of the sensitivity parameters, by computing our results with the ERF best estimate and with the lower and upper bound of the confidence intervals.

Data availability

The input data to this analysis is publicly available at https://esgf-node.llnl.gov/search/input4mips/. The data output in this study, that is, the raw data of figures, can be accessed under the folder 'Outputs': https://github.com/nikibraz/definitions_climateneutral_aviation.git.

Code availability

The code used to generate figures and tables is available at https://github.com/nikibraz/definitions_climateneutral_aviation.git and will be made publicly available upon acceptance.

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Author contributions

N.B., A.P. and J.W. designed the study. N.B. performed the analysis with support from J.W. N.B. and J.W. wrote the manuscript. All authors edited the manuscript and engaged in ongoing discussions.

Competing interests

The authors declare no competing interests.

Additional information

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