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OVERVIEW

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A "greenhouse gas balance" for aviation in line with the Paris Agreement

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Abstract

The effects of aviation on climate pose unique policy challenges. A large fraction of the CO_2 emissions (65%) is international and not (explicitly) included in the Paris Agreement. The interpretation of Article 4.1 on achieving a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" is ambiguous in the context of aviation because of the substantial non-CO_2 effects associated with the sector. For the achievement of the temperature goal in Article 2, both CO_2 and non-CO_2 effects are important. The non-CO_2 effects contribute 66% of the sectoral total climate effect (in terms of Effective Radiative Forcing; ERF) at present, with significant uncertainties. The largest of these non-CO_2 effects, contrail-cirrus and the net-effect of NO_x, are not caused by direct greenhouse gas emissions, representing another ambiguity as to whether they should be included in the balance concept. We discuss the role of aviation in the context of the Paris Agreement, and present illustrative calculations of a hypothetical aviation "greenhouse gas balance." Several questions are addressed: Which components should be included? If an aggregate of components is adopted for the "balance," which metric should be used? How can the large differences in timescales as well as the large intrinsic underlying ERF uncertainties be handled? We demonstrate that these choices result in very different requirements for CO_2-removal from the atmosphere and different temperature outcomes over time. The article provides policymakers with an overview of issues and choices that are important regarding which approach is most appropriate for defining and achieving a greenhouse gas balance for aviation in the context of the Paris Agreement.

This article is categorized under:

- Policy and Governance > International Policy Framework
- Climate and Development > Knowledge and Action in Development
- Paleoclimates and Current Trends > Climate Forcing

KEYWORDS

aviation, greenhouse gas balance, net-zero, non-CO_2 forcing, Paris Agreement

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1 | INTRODUCTION

The Paris Agreement provides ambitions and a direction for globally coordinated climate policies, and its Article 2 contains the main goal: "*holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*." In the context of this long-term temperature goal, Article 4.1 further contains a mitigation goal of achieving "*a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty*." In 2018, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR1.5) (IPCC, 2018) focused on what would be required to achieve the most ambitious temperature goal of the Paris Agreement. A main finding was that scenarios that limit warming to 1.5°C with no or limited overshoot, reach net zero CO_2 emissions by around mid-century, followed by net negative CO_2 emissions thereafter. More recently, the Working Group III contribution to the IPCC 6th Assessment Report (IPCC, 2022) found similar results for the timing of global net zero CO_2 emissions, while for net zero greenhouse gas emissions there were two sub-categories for the scenarios with no or limited overshoot of 1.5°C; one sub-category reaching net zero greenhouse gas emissions in the second half of the century and one sub-category that does not reach net zero greenhouse gas emissions during this period. However, what constitutes a "greenhouse gas balance," as given in Article 4.1, is not clear, and several different interpretations and formulations have been used and discussed (e.g., Allen et al., 2022a; Dray et al., 2022; Fuglestvedt et al., 2018; Rogelj et al., 2015; Rogelj et al., 2021).

More than 130 countries have set, or are considering, net zero goals (Höhne et al., 2021), as have over 7000 companies and over 1100 cities.[1] These national ambitions are referred to in many of the Nationally Determined Contributions (NDCs) submitted by the countries. The parties to the Paris Agreement are the countries, who are only responsible for emissions within their own territorial borders, and international aviation and international shipping emissions are not mentioned in the agreement. This differs from the Kyoto Protocol (Article 2.2) where international aviation and shipping were explicitly mentioned, and Annex 1 countries were required to pursue limitation or reduction of greenhouse gas (GHG) emissions not covered by the Montreal Protocol through the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO). In addition to the unclear role of ICAO and IMO in the Paris Agreement, the physical impacts of aviation on climate are complex and heterogeneous, involving a diverse set of non-CO_2 forcing agents in addition to CO_2 from its fossil fuel consumption.

Against this background, we introduce the role of international aviation, which represents 65% of the current annual CO_2 emissions from the entire sector (Fleming & Lepinay, 2019) in the context of the ambitions of the Paris Agreement and discuss the state-of-the-art on the various climate effects of aviation.[2] We then explore how the concepts of "balance" and "net zero" can be applied to international aviation, and its potential contributions to the achievement of Article 4.1 and Article 2 of the Paris Agreement.

2 | THE ROLE OF AVIATION IN THE PARIS AGREEMENT

The omission of an explicit mention of international aviation or ICAO in the Paris Agreement introduces ambiguity in what part it should play in achieving the global goals. But while not explicitly mentioned in the text, for Article 4.1 to have any function in supporting Article 2, it must apply to *all anthropogenic* warming emissions as a necessary milestone for achieving the temperature goal.

Emissions from *domestic* aviation are included in some of the NDCs submitted by the parties of the Paris Agreement. According to the Climate Action Tracker,[3] none of the 193 NDCs include a specific target for international aviation. As an example, the UK's legally binding Sixth Carbon Budget of 2021, which aims to reduce CO_2 emissions by 78% by 2035, compared with 1990 levels, does include emissions from both international aviation and shipping.[4] However, these emissions are not included in the UK's NDC, since the UN convention is to report these separately. Considering the text of the Paris Agreement, as well as current policy developments, it is therefore unclear how international aviation is meant to, and will, contribute to meeting the goals of the Paris Agreement.

Since 2010, ICAO has had two aspirational goals related to climate and CO_2; a 2% annual fuel efficiency improvement through 2050, and a carbon neutral growth goal from 2020 onwards, as established at ICAO's 37th Assembly in 2010, and most recently reiterated at its 40th Assembly in 2019.[5] The "carbon-neutral growth goal, 2020" (CNG2020), states that international aviation emissions of CO_2 should not grow above 2020 levels. To achieve these

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aspirational goals, ICAO is pursuing a range of measures that includes aircraft technology improvement, operational improvements, sustainable aviation fuels, and market-based measures. It is envisaged that the CNG2020 goal is to be achieved mainly by offsetting CO_2 emissions outside of the sector with the market-based mechanism "CORSIA" (Carbon Offsetting and Reduction Scheme for International Aviation). The baseline year of 2020 was subsequently revised to being 2019 by the ICAO Council, in light of the COVID-19 pandemic, for the implementation pilot phase[6] from 2021 to 2023. These goals have not changed since 2010, and in response to the Paris Agreement and the UN Sustainable Development Goals, among other things, the ICAO 2019 40th Assembly recognized that "*… goals of more ambition are needed to deliver a path for sustainable aviation*" and requested the ICAO Council to "*explore a long-term global aspirational goal for international aviation in light of the 2°C and 1.5°C temperature goals of the Paris Agreement*." Greater ambition and disruptive technology development for the sector has been advocated (Kallbekken & Victor, 2022). ICAO has recently published a report on the feasibility of a long-term aspirational goal for international aviation CO_2 emissions[7] for which three scenarios were formulated with increasingly innovative levels of technology development for low carbon fuels. Informed by this report, ICAO adopted a net zero aspirational goal for carbon emissions by 2050[8] at its most recent 41st Assembly (October 2022). All three scenarios indicated that there would be residual fossil CO_2 emissions from international aviation out to 2070, such that the ambition of ICAO's net zero CO_2 goal will require either further emissions reductions, or CO_2 removals, although this was not acknowledged in the Assembly Resolution. At present, neither a method for the monitoring of progress toward these goals, nor the role of non-CO_2 emissions have been agreed.

The issue of governance of international aviation was recently touched upon by the IPCC's WGIII AR6 report in the Summary for Policymakers, which said "Improvements to national and international governance structures would further enable the decarbonization of shipping and aviation (*medium confidence*)" (and was dealt with in more detail in Chapters 10 and 14 of the same report; IPCC, 2022). An analogue of an NDC to the international emissions could prove difficult through ICAO. There is no mechanism for binding state targets through State Action Plans, since the primary mechanism of ICAO is "Standards and Recommended Practices" (SARPs) for state-implementation of for example, emission regulations.

3 | NET ZERO CONCEPTS AND ARTICLE 4.1 OF THE PARIS AGREEMENT

Article 4.1 of the Paris Agreement contains several elements that need further considerations (e.g., Allen et al., 2022a; Fankhauser et al., 2022; Fuglestvedt et al., 2018; Rogelj et al., 2021; Schleussner et al., 2016; Wigley, 2021), especially for aviation with its complex set of climate effects, as discussed below. In particular, the statement on "greenhouse gas balance" is subject to interpretation, and clarifications are needed to make it operational for climate policies at global, national and sectoral levels.

The main goal of the Paris Agreement is formulated, in Article 2, in terms of a change in the *global average temperature* relative to pre-industrial levels. This could indicate that "balance" refers to reaching a stable temperature. As pointed out by Fuglestvedt et al. (2018), a balance in emissions could thus, in one interpretation, correspond to those levels of greenhouse gas emissions that stabilize the global mean temperature at some given level (and subject only to natural climate variability). However, the Paris Agreement makes no explicit reference to whether the global mean temperature is to be stabilized at some level above pre-industrial levels, or whether it has to peak and then decline which is also an interpretation of the Paris Agreement (e.g., Schleussner et al. (2016)). Article 4 refers to a "global peaking of greenhouse gas emissions" but not a peaking of global temperature. While various interpretations of "greenhouse gas balance" are possible (as discussed, e.g., by Allen et al., 2022a; Fuglestvedt et al., 2018; Tanaka & O'Neill, 2018), a common view in the scientific community is that the "balance" can be interpreted and made operational in terms of net-zero *CO_2-equivalent emissions* based on the global warming potential for a 100-year time horizon (e.g., IPCC, 2022; Rogelj, 2023; Rogelj et al., 2021; van Soest et al., 2021). In addition to the question as to which components to include, such an aggregation of different greenhouse gases opens the question of how to calculate CO_2-equivalent emissions by weighting the different gases. In particular, the meaning and outcome of net-zero GHG emissions varies with the chosen emission metric, and the climate effect of maintaining this "balance" over time will also vary depending on the chosen emission metric (Allen et al., 2022a; Fuglestvedt et al., 2018; IPCC, 2021; IPCC, 2022; Rogelj et al., 2021). Emission pathways using CO_2 removal to reach and sustain GWP_{100} based net zero GHG will result in declining global temperature (IPCC, 2021; IPCC, 2022; Rogelj et al., 2021).

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Net zero CO_2, net zero GHG, carbon neutrality, GHG neutrality, climate neutrality have become much-used concepts in climate policy, often going undefined, and used interchangeably. "Neutral" and "climate neutral" are sometimes used synonymously for net-zero CO_2 and net-zero greenhouse gas emissions. For example, France's strategy applies the term "carbon neutrality" but includes all GHGs,[9] while the EU connects neutrality and net zero in the way they phrase their target: "The EU aims to be climate-neutral by 2050—an economy with net-zero greenhouse gas emissions."

The IPCC's Sixth Assessment Report Glossary gives definitions for four related terms (Matthews et al., 2021)[10]:

> *Net zero CO_2 emissions*: "Condition in which anthropogenic carbon dioxide (CO_2) emissions are balanced by anthropogenic CO_2 removals over a specified period."
> *Net zero greenhouse gas emissions*: "Condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period. The quantification of net zero GHG emissions depends on the GHG emission metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric."

At a global scale, the net zero concepts above are equivalent to *carbon neutrality* and *greenhouse gas neutrality*, respectively. At sub-global scales, the terms net zero CO_2 or GHG emissions are generally applied to emissions and removals under direct control or territorial responsibility of the reporting entity, while carbon or GHG neutrality generally includes emissions and removals within and beyond the direct control or territorial responsibility of the reporting entity.

How does the complex mix of climate effects of human activities—and in particular from aviation—fit into these various concepts for net zero? Human induced global warming is a consequence of emissions of a wide range of greenhouse gases with different characteristics, as well as land use change and emissions of aerosols and precursor gases. In terms of radiative forcing since pre-industrial times, CO_2 is the dominating gas, with significant contributions also from methane (CH_4) and nitrous oxide (N_2O), while various halogenated gases also add to the total warming from human activities. Reducing CO_2 emissions down to net zero would halt further CO_2-induced warming, but the effects of the already anthropogenically enhanced atmospheric CO_2 will last for millennia. On the other hand, constant emissions of short-lived climate forcers (such as black carbon (soot) and CH_4) would not result in further warming from these components and reducing them would result in reduction in their warming contributions (e.g., Allen et al., 2022b and references therein).

As pointed out by Allen et al. (2018) and Fuglestvedt et al. (2018), an alternative approach to interpret and define balance would be to counterbalance only the long-lived GHGs while keeping the emissions of short-lived components constant, since near-stabilized emissions of these components would add no further temperature increase. Application of the GWP* concept by Allen et al. (2018) would lead to a different weighting between non-CO_2 and CO_2 from aviation since CO_2-equivalent warming from GWP* is based on the rate of change of emission of short-lived forcers. A stable forcing from non-CO_2 is equivalent to zero CO_2 emissions, and no further increase in temperature, while a decreasing rate of short-lived forcer emissions can be equated to removals of CO_2, since the contribution to temperature change decreases. This behavior of non-CO_2 forcing agents differs markedly from CO_2, for which cumulative emissions matter, such that any additional emission of CO_2 results in a temperature increase.

Article 4.1 of the Paris Agreement refers to "greenhouse gases" but without specifying which gases this includes. A literal interpretation of the words "anthropogenic emissions by sources and removals by sinks of greenhouse gases" would exclude aerosols, and aerosol precursor gases, from the group of components included in the evaluation of "balance," and potentially also greenhouse gases formed from precursor emissions (e.g., ozone). The Kyoto Protocol adopted a basket of six gases or groups of gases that are directly emitted: CO_2, CH_4, N_2O, SF_6, perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs). Later, NF_3 was added to the basket of "Kyoto II." It may be argued that this group of gases could by default be included in the "greenhouse gas balance" addressed in Article 4.1.

Net zero CO_2 and net zero GHG are two different concepts with different temporal behavior. While the need for, and timing of, net zero CO_2 emissions was a main message from IPCC SR1.5 and recently supported by AR6 WGIII, the timing of net zero GHG was also given for the Kyoto gases, aggregated by using GWP_{100}. Net zero GHG was found to occur 7–39 years later than net zero CO_2 in the assessed cost-optimal 1.5 and 2°C scenarios (IPCC, 2022) that reach net zero GHG before 2100, and some scenarios do not reach net zero GHG before 2100 depending on how the Integrated Assessment Models (IAMs) are constructed, how the climate target is imputed in the models and whether the scenario is overshooting a warming target (Johansson, 2021). The difference in timing between net zero CO_2 and net zero GHG

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is due to the need for larger amounts of CO_2 removal to compensate for remaining emissions of non-CO_2 which will happen later since to achieve net zero GHG emissions, CO_2 emissions first need to reach net zero and afterwards need to become net negative.

As can be seen from the scenarios assessed by the IPCC and as also pointed out in the literature, net zero CO_2 or net zero GHG are not endpoints for mitigation strategies. Rogelj et al. (2021) discuss aspects related to these concepts and point out that road maps are needed with milestones, explanation of what policies will be implemented, and the monitoring, reporting and verification systems that will be used to assess progress, and whether net zero be maintained or if it is a step toward net negative CO_2 emissions. For international aviation CO_2 emissions, the long-term aspirational goal under discussion by the ICAO would ultimately require elaborations on all the aspects addressed above.

4 | CLIMATE FORCERS FROM AVIATION

Among the various economic sectors and human activities contributing to global warming, aviation stands out as a sector with several unique characteristics, beyond those mentioned above in terms of attribution and responsibilities for emissions and international aviation's role in the Paris Agreement. Aviation operations contribute to anthropogenic climate change via a complex set of processes caused by emissions in the upper troposphere and lower stratosphere that lead to a net surface warming, calculated to be approximately 4% of the overall warming to date for the sector as a whole (i.e., international and domestic aviation) (Klöwer et al., 2021). The sector was also fast-growing until the covid pandemic caused strong reductions in the activity (Le Quéré et al., 2020), with CO_2 emissions increasing by a factor of 6.8–1034 $TgCO_2$ $year^{-1}$ over the period 1960–2018 (Lee et al., 2021).

The main climatic effects from aviation are from emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), water vapor (H_2O), soot and sulfate aerosols, and increased cloudiness due to formation of linear contrails and subsequent cirrus clouds (contrail-cirrus, CC). A recent assessment of the overall effect of aviation on effective radiative forcing (ERF) was approximately 101 mW m^{-2} (5%–95% likelihood range of 55, 145 mW m^{-2}), some 3.5% of global ERF (Lee et al. (2021); see Figure 1). It was determined that the largest net warming terms were from contrail-cirrus (57.4 mW m^{-2}), followed by CO_2 (34.3 mW m^{-2}) and the net NO_x effect (17.5 mW m^{-2}). Aviation aerosols interact with radiation both directly and indirectly via clouds. The direct effect is assessed to be small. In contrast, best estimates of the ERFs from aviation aerosol-cloud interactions for soot and sulfate could not be determined (Lee et al., 2021). The non-CO_2 forcings, while estimated to be presently 66% of the total, were far more uncertain than that from CO_2, contributing 8 times more to the uncertainty (Figure 1).

The study by Lee et al. (2021) applies a backward-looking perspective, that is, accounting for historical emissions and quantifying the present-day (2018) effective radiative forcing (relative to the start of the aviation activity). This is important for understanding the contributions of the broad set of effects to the overall impact of the sector and the sector's impact on total human induced warming to date. It is also a starting point for modeling of possible future climate impacts of this sector. Scenarios for the aviation sector are scarce in the literature, but the shared socioeconomic pathways (SSPs) framework (O'Neill et al., 2017), include aviation as a separate sector.

Figure 2 shows the projected aviation CO_2-emissions under five of the SSPs (formulated prior to the covid pandemic, thus not reflecting the downturn in traffic in 2020), the resulting CO_2-induced global warming and the total global warming (i.e., including non-CO_2 effects) up to 2100.

In the SSPs, the global CO_2 emissions (i.e., all sources/sectors) (not shown), span a broad range of possible future emissions, from more than a factor of 3 increase from 2015 levels in SSP5-8.5 to reductions to below net zero global CO_2 emissions in the 2050s and 2070s in SSP1-1.9 and SSP1-2.6, respectively (Riahi et al., 2017). A large spread is also seen for aviation emissions, and in the consequent contribution to global warming (Figure 2). However, while the general evolution of the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios are similar for aviation and total anthropogenic emissions, a key difference exists for the lowest CO_2 emission scenarios, SSP1-1.9, SSP1-2.6, which are consistent with the temperature ambitions of the Paris Agreement. Specifically, total anthropogenic CO_2 emissions reach net zero in the 2050s and 2070s in SSP1-1.9 and SSP1-2.6, respectively, becoming net negative thereafter, whereas there are substantial remaining emissions of CO_2 from aviation at these points in time (0.2 and 0.7 Pg CO_2 in SSP1-1.9 and SSP1-2.6, respectively, in 2050). Thus, if aviation is aiming for net zero CO_2 emissions, large additional reductions (beyond what is included in the SSP scenarios) or large amounts of CO_2 removal are needed. Furthermore, this challenge will increase if non-CO_2 effects are included in the net zero target, as illustrated by the difference in temperature response under the

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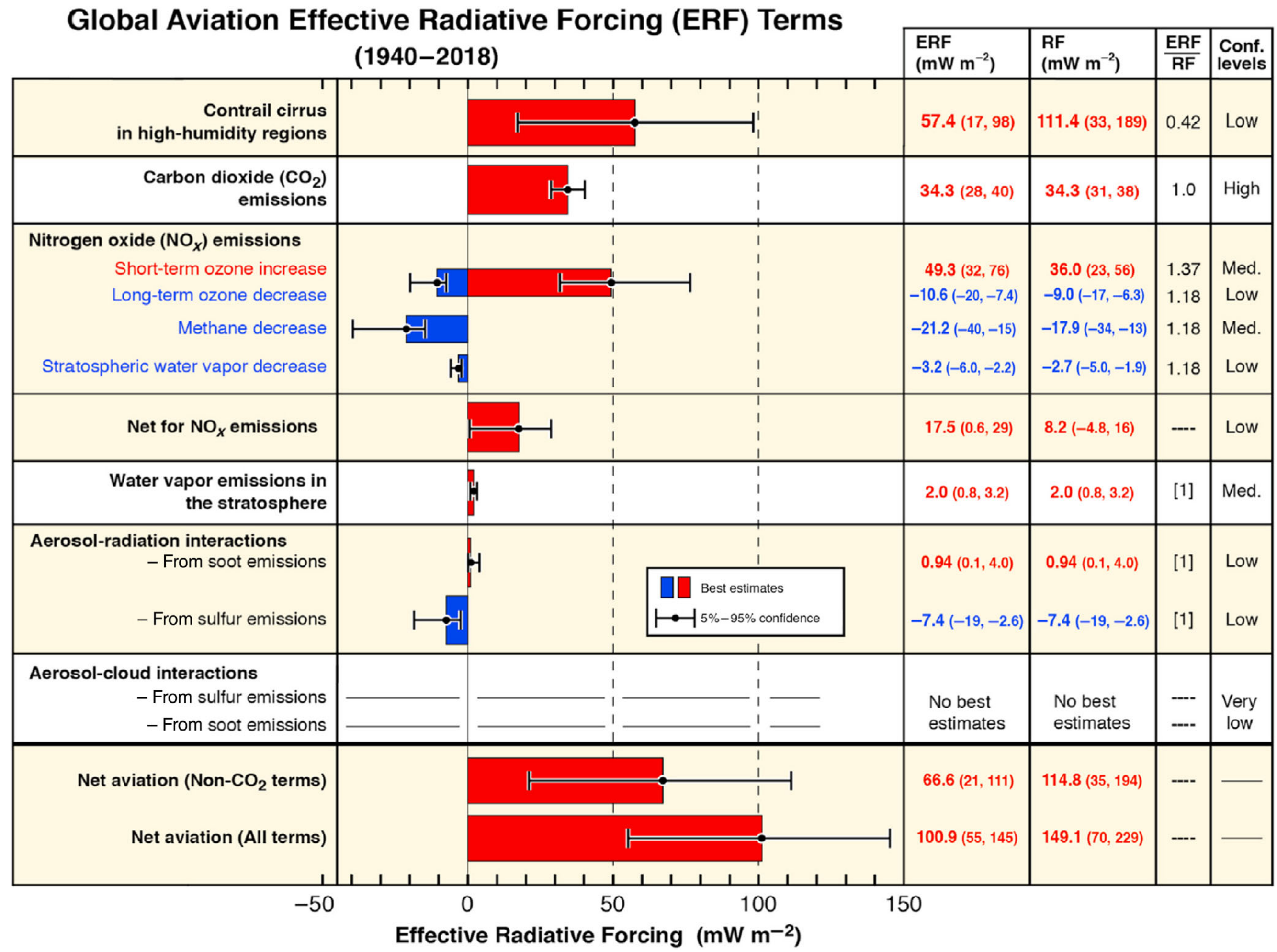

FIGURE 1 Best-estimates for climate forcing terms from global aviation from 1940 to 2018 (from Lee et al., 2021). The bars and whiskers show ERF best estimates and the 5%–95% confidence intervals, respectively. Red bars indicate warming terms and blue bars indicate cooling terms. Numerical ERF and RF values are given in the columns with 5%–95% confidence intervals along with ERF/RF ratios and confidence levels.

SSP scenarios when accounting for CO_2 only versus all emissions from aviation (in Figure 2a,b). However, inclusion of these effects also triggers several further questions that need to be addressed.

5 | WHICH COMPONENTS IN THE "BALANCE" FOR AVIATION?

The complex and heterogeneous set of effects on forcing by aviation leads to the question "Which components should be included in the 'GHG balance' for aviation to be consistent with the ambitions of the Paris Agreement?" The contribution from aviation to climate warming does not neatly fit the "greenhouse gas balance" concept in the Paris Agreement or "net zero GHG emissions" definitions given above. Moreover, it is not explicitly given how cooling agents or cooling effects should be considered in this context. Here we elaborate on the climate-relevant emission from aviation in light of Article 4.

The only direct GHG emissions from aviation are CO_2 and H_2O. Following the text of Article 4.1, the obvious gas to be considered from aviation is CO_2. Since the role of direct emission of H_2O is minor in a global perspective, water vapor is usually not included in climate policies. But in the case of aviation, this gas plays a different role since it is emitted directly into the dry stratosphere. While currently imposing only a small change to the global energy balance relative to other aviation emissions, the effect could be substantial if the future aircraft fleet were to include higher-flying supersonic aircraft (IPCC, 1999; Matthes et al., 2022). A transition to hydrogen as fuel could also lead to increased importance of water vapor.

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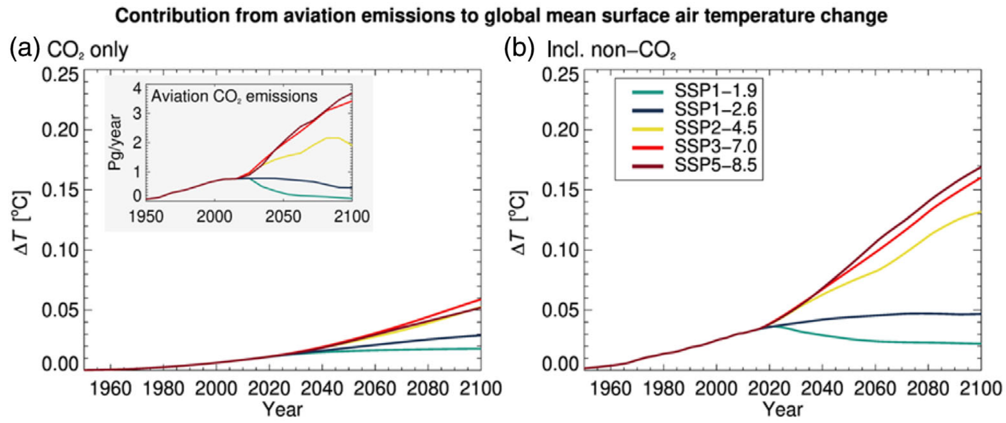

FIGURE 2 Effects of total (international and domestic) aviation emissions on global mean surface temperature from (a) CO_2 only and (b) from CO_2 plus non-CO_2 (contrail-cirrus, BC, SO_2, NO_x). Insert shows CO_2 emissions from aviation in the selected scenarios. Calculated for five selected SSP scenarios and best estimates of ERF in 2018 from Lee et al. (2021) using the CICERO Simple Climate Model (Nicholls et al., 2020) following the methodology from Skeie et al. (2017). Note that in this methodology, future contrail-cirrus radiative forcing is derived through scaling with CO_2 emission as a proxy for fuel use, assuming continued fossil fuel usage. Substitutions to alternative fuels (such as may underlie the SSPs) can affect the relationship between fuel burn and contrail formation. By not capturing such changes in our calculations, our estimates of contrail-cirrus contribution to warming could be over- or underestimated.

Nitrogen oxides ($NO_x = NO + NO_2$) do not themselves induce radiative forcing, but they affect the concentrations of two important greenhouse gases, methane (CH_4) and tropospheric ozone (O_3), via chemical reactions in the atmosphere. Emissions of NO_x from aviation cause a short-term increase in ozone, followed by a long-term decrease, as well as decreases in methane and stratospheric water vapor. The *net* effect of this to date is a net warming from aviation emissions of NO_x (Lee et al., 2021). However, Skowron et al. (2021) have pointed out that this net effect could become negative (i.e., cooling) in future decades, depending on both aviation and background emissions levels of ozone precursors. Thus, a question of interpretation of the Article 4.1 arises, namely whether only *direct* greenhouse gas emissions are included? Another question that needs to be addressed is "Should only *warming components* be included?" and furthermore, "should the *net* effect of warming and cooling effects be used if NO_x is to be included?" Regarding the indirect effects on tropospheric O_3 and stratospheric H_2O, there is some guidance from the fact that these effects were covered by the Kyoto Protocol via the inclusion in the GWP for CH_4 used under the UNFCCC. The net effect of NO_x is included in calculations and examples below since the associated cooling components are physically inseparable from the warming effect of short-term ozone.

Emissions of SO_2, on the other hand, which are rapidly oxidized to sulfate, have strong cooling effects, and are included in the calculations of future global temperature change from aviation (Figure 2). However, SO_2 is not included in the illustrative net zero examples given below on the grounds that achieving GHG gas balance is meant to limit global warming and support Article 2 of the Paris Agreement. Inclusion of SO_2 in a net zero GHG or balance concept could also be seen as opening for use of solar radiation modification (SRM), which is not supported by the text of the Paris Agreement.

One of the effects that has received much attention—both scientifically and also from the general public—is the formation of contrail-cirrus (CC). These are ice crystal clouds, formed around aircraft soot particles and water vapor from the engine. The emitted water vapor triggers an initial nucleation of water droplets on soot particles that subsequently freeze. These initial droplets can rapidly increase in size from an ice supersaturated background atmosphere. Thus, it is not clear if this effect is covered by "GHG balance" since it is caused by both aerosols (soot) and a gas (H_2O), the water largely being derived from the background atmosphere, but the forcing is not from a gas as such. In addition, the net forcing of contrail-cirrus is the sum of short-wave cooling effects and long-wave warming; similarly to the net NO_x effect, the net effect (warming) is included in the net zero example below, since the cooling effect is inseparable from the warming.

As clearly shown by Lee et al. (2021) there are large variations in the uncertainties related to the estimates of the various radiative effects of aviation. In addition, there are also large differences in the timescales on which these components operate. A significant residual (approximately 20%) of CO_2 persists for millennia after emission, and any

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continued emission therefore accumulates in the atmosphere. NO_x and contrail-cirrus, on the other hand, have lifetimes of the order of hours to days. These differences in time scale also open questions over how to value the impacts of the different forcers over time (e.g., Fuglestvedt et al., 2003; Fuglestvedt et al., 2010) and have implications for choice of metric for aggregating emissions to net zero GHG (Allen et al., 2022a; IPCC, 2021; Rogelj et al., 2021). As an example, a recent study by Dray et al. (2022) considered a broad set of forcing components from aviation (gases and aerosols, contrails) in their net-zero calculations based on GWP_{100} (and also GWP for 20 and 500 years) without discussing how this aligns with Article 4.1 of the Paris Agreement. The aggregation issue is also discussed further below.

The Paris Agreement text is not explicit about whether the balance between sources and sinks is mandated at a global or national level. It states that "parties aim to … achieve a balance …." Whereas the text does not specify whether this applies individually or jointly, by requiring differentiation of efforts, and by allowing for trade in emissions, the Paris Agreement does not imply that each country has to achieve a greenhouse gas balance within its territorial borders. From a geophysical and climate system perspective, it is the ultimate balance at a global level that is needed to support Article 2. There are significant differences in anticipated residual emissions across sectors and countries, and significant differences between countries also in the potential for and cost of carbon dioxide removal (Lee, Fyson, & Schleussner, 2021). Some countries have large emissions from agriculture, heavy industry, and so forth, that may be costly or difficult to reduce to zero. For most sectors the CO_2 removals that balance residual emissions will have to take place out-of-sector (e.g., Fankhauser et al., 2022). This points to the need for global coordination, which can take the form of a system for trading where both emissions and removals of CO_2 would be included. An additional point regarding emissions from international aviation is that they are, as discussed, not attributed to individual countries.

ICAO has implemented its Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), a market-based measure, as a part of its broader initiative to achieve carbon-neutral growth from 2020 (i.e., no further increase in CO_2 emissions). It takes a phased approach, and only becomes mandatory in 2027. So far, 115 states are participating in the voluntary phases. The reductions are out-of-sector measures from the purchase of certified offsets. Most of the offsets certified are "avoidance" offsets. Such offsets have particular problems of being verifiable, in the sense of additionality (Becken & Mackey, 2017). For any continued fossil-fuel emissions of CO_2, permanent removals represent the best quality "offset." These are available in limited quantities and are currently much more expensive than avoidance or biomass plantation offsets.

In addition to this *sectoral* dimension behind a global GHG balance, there is also a *temporal* dimension. Some sectors or countries may achieve net zero early, while others may do so later. As pointed out (e.g., Fuglestvedt et al., 2018; IPCC, 2022; Rogelj et al., 2021), all this must add up to obtain a balance at the global scale, with a timing consistent with what is needed for achieving the temperature goal. Obviously, the coordination of contributions toward a global balance would require a well-functioning international and cross-sectoral collaboration and coordination. An example of the quantification of the contributions is the annual accounting exercise of UNEP's Emissions Gap Reports (UNEP, 2021; UNEP, 2022) that take countries' NDCs and chart progress toward temperature goals. Should ICAO agree on a long-term goal for carbon emissions, similar issues will arise in terms of how to chart progress toward the goal and individual states, or operators' responsibilities.

Different interpretations of "balance" have different implications for what is needed in terms of negative emissions (e.g., Allen et al., 2022a; Fuglestvedt et al., 2018). If the common GWP_{100}-based interpretation is applied, as discussed above, achieving a "balance" in GHG emissions implies that any residual and difficult-to-abate emissions of CO_2 and non-CO_2 gases need to be compensated for, primarily by permanent CO_2 removals. To determine the magnitude of CO_2 removals needed, some form of aggregation of the CO_2 and non-CO_2 emissions to a common scale is needed. If "balance" is interpreted in terms of net-zero *CO_2-equivalent emissions*, such an aggregation of different GHGs opens the question on how to calculate CO_2-equivalent emissions by weighting the different gases. As a result of this, the meaning and quantification of net zero GHG emissions varies with the chosen emission metric, and consequently the climate response to maintaining this "balance" over time will also depend on the chosen metric (Fuglestvedt et al., 2018; IPCC, 2022; Rogelj et al., 2021). The text of the Paris Agreement itself does not indicate how this aggregation is done, or what metric to use. But later, as part of the Paris Rulebook agreed in Katowice in 2018, (Decision 18/CMA.1, annex, paragraph 37) the global warming potential over a time horizon of 100 years was decided as the default metric to report aggregated emissions and removals of greenhouse gases. In addition, parties may use other metrics to report supplemental information. For aviation, various metrics have been applied in the literature (Dahlmann et al., 2016; Dray et al., 2022; Fuglestvedt et al., 2010; Klöwer et al., 2021; Lee et al., 2010; Lee et al., 2021; Lund et al., 2017), but no specific metric has been formally adopted for this sector. As discussed in several papers and assessments reports

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(e.g., IPCC, 2013; IPCC, 2021; IPCC, 2022), it is up to the policymakers to decide which emission metric is most applicable to their needs and the most appropriate metric depends on the context and the policy goal it is meant to support.

6 | QUANTIFYING THE AVIATION "BALANCE" AND ITS TEMPERATURE EFFECTS

To illustrate how various metric choices and ways of combining and aggregating emissions from aviation will affect the amount of CO_2 removal required and the following implied temperature response, we choose SSP1-2.6 total aviation emissions for 2050 as an example and calculate the net zero GHG emissions (i.e., "greenhouse gas balance") for a selected set of components using different emission metrics from Lee et al. (2021). As discussed, contrail-cirrus and soot are not obvious candidates for inclusion since these are not forcers in gaseous form but are included in this example since they generally are included in assessments and quantifications of climate effects of aviation. We have left out the cooling component SO_2 in the greenhouse gas balance example below, since balance as stipulated in Article 4 is meant to support the temperature goals of Article 2 (as discussed above). Nonetheless, we have included the "net NO_x" effect and contrail-cirrus (CC), both of which have cooling components, since the warming and cooling components are hard to separate. This choice reflects one of the ambiguities of Article 4.1. For the different selection of metrics, we calculate the total CO_2-equivalent emissions in 2050 from the aviation sector—which then need to be balanced by CO_2 removal to achieve net zero greenhouse gas emissions. Finally, we calculate the temperature impacts over time resulting from these cases of "net zero emissions" for aviation and show how this depends on choice of metric.

Figure 3a shows total CO_2-equivalent emissions for 2050 from aviation based on SSP1-2.6 using the emission metrics global warming potential (GWP) and global temperature-change potential (GTP) for various time horizons. For both metrics, a shorter time horizon gives more weight to short-lived components relative to the reference gas CO_2. The total CO_2-equivalent emission based on GWP_{20} is almost four times larger than what is obtained using the GTP_{100} (Figure 3a). This large spread leads to very different perceived needs for implied CO_2 removals to counterbalance these CO_2-equivalent emissions (Figure 3b)—from 824 to 3113 $TgCO_2$. Furthermore, the uncertainties in aviation ERF (Figure 1) translate to uncertainty in the emission metrics. This is demonstrated by the high and low estimates in Figure 3b, where the required amounts of CO_2 removals are calculated based on respective metrics values derived using the upper and lower ERFs from Lee et al. (2021).

These four cases of achieving a net zero greenhouse gas emissions for aviation would, in turn, lead to different effects on global temperature since different amounts of CO_2 removals are needed to counterbalance the CO_2-equivalent emissions. Figure 4a shows the temperature effect if the set of emissions included in the balance are kept

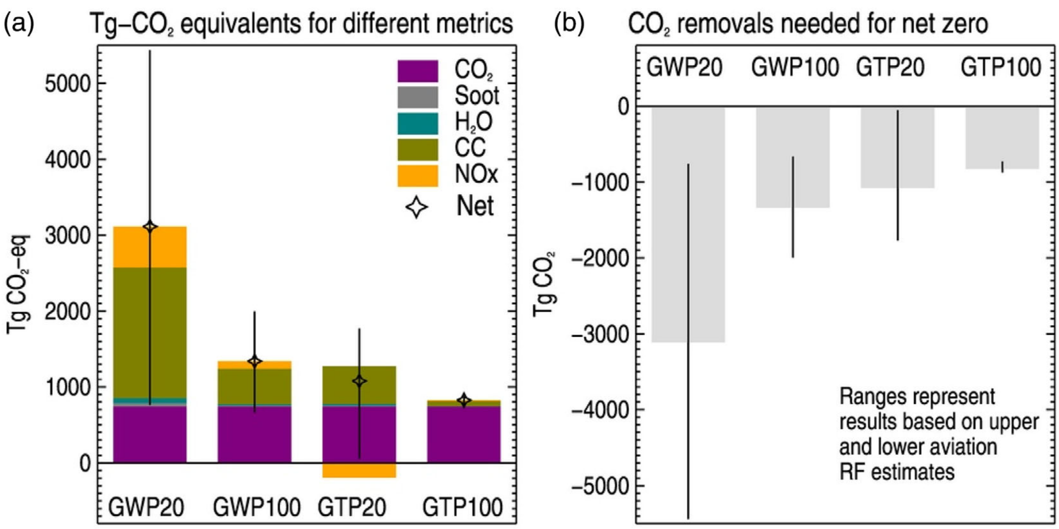

FIGURE 3 (a) Total CO_2-equivalent emissions for SSP1-2.6 in 2050 calculated with different metrics and (b) corresponding amounts of CO_2 removal for compensation. In addition to the central estimate, low and high estimates are calculated with emission metrics derived using the best estimate and lower and upper range of ERF from Lee et al. (2021).

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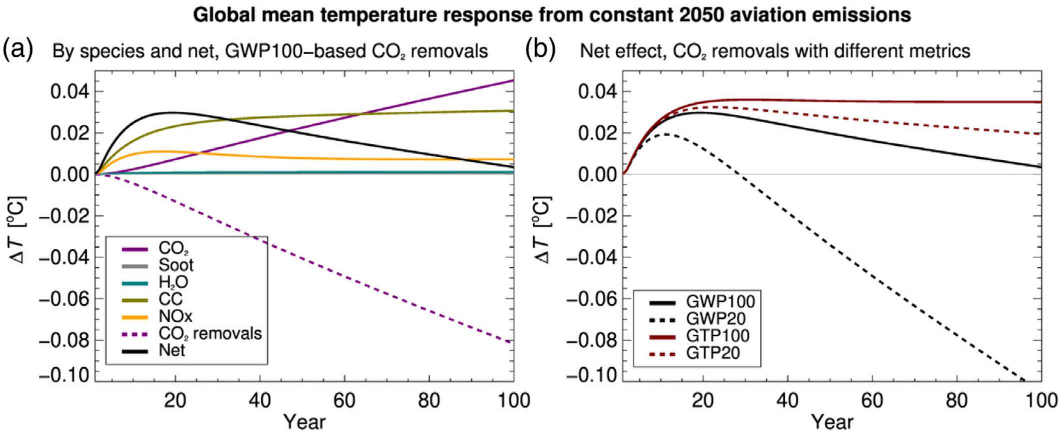

FIGURE 4 Global mean temperature response following constant emissions at the 2050 level (for SSP1-2.6). (a) For individual components and net response, with CO_2 removals for balance calculated with GWP_{100} and (b) net response when the amount of CO_2 removals required for balance is calculated with different metrics. The temperature effects are calculated using the concept of absolute temperature change potential (AGTP), an emission-metric based emulator of climate response, following the approach by Lund et al. (2020) and with the AGTP values consistent with Lee et al. (2021).

constant at the net zero level. The net effect will be a warming the first decades—due to the effects of short-lived non-CO_2 components, and on a longer century scale the net effect is slowly reduced toward zero when the effect of the CO_2 removals builds up. This shows how the CO_2 removals counteract the short-lived emissions on a much longer timescale than that which the short-lived forcers operate on. This is a consequence of trading across components using GWP_{100}. Since use of different metrics lead to different amounts of CO_2 removal required, the choice of metric will affect the net temperature effect of the set of components included in the "balance," which is illustrated in Figure 4b. They all show an initial warming effect, but the decline toward zero and the negative temperature response varies, with GWP_{20} having the largest negative temperature response due to the large amount of CO_2 removals needed in that case.

In these illustrative calculations we have implicitly assumed an unchanged fuel mix in the aviation sector, that is, we consider the residual fossil fuel emissions. In reality, the technology and use of fuels, and hence also the relation between CO_2 and non-CO_2 forcings, will change in the future. For instance, if there is continued increase in air traffic demand, part of that demand may mainly be filled by sustainable aviation fuel (SAF) and liquid hydrogen (LH_2). While SAF is considered carbon neutral, there will still be NO_x emissions. Hence, just considering the residual fossil fuel will underestimate the net NO_x effect, since the SAF fraction will also have NO_x associated with it. The same goes for LH_2, where NO_x will be generated. Similar considerations also apply to contrail-cirrus, where a switch from fossil fuel to SAF has been shown to reduce the climate impact of the contrail-cirrus, but where more complicating factors over LH_2/SAF/fossil differential come into play. While such details are beyond what can be captured in these simplified examples and are also not readily available in the SSP scenarios, these considerations demonstrate that updated and more detailed scenarios could significantly strengthen the basis for assessments of the role of this sector in the context of the Paris Agreement.

The IPCC, 1999 Aviation and Climate report introduced the concept of the Radiative Forcing Index (RFI) to quantify the ratio of the total forcing (CO_2 + non-CO_2) to the CO_2 forcing. However, this is a backward-looking metric, not intended to be a metric for calculation of CO_2-equivalent emissions. Despite this, the RFI is being used widely in-flight emissions calculators and assessments of climate impacts for scaling up CO_2 emissions to account for non-CO_2 effects (see e.g., overview in Barret, 2020). The RFI, as shown in several papers and assessments, is not suited either for emissions equivalency calculations or for policy making when considering mitigation (Forster et al., 2006; Forster et al., 2007; Fuglestvedt et al., 2010).

7 | CONCLUSION

The literature is clear that net zero is not an endpoint for global emission pathways for limiting global warming to 1.5 or 2°C in the longer term (e.g., Rogelj et al. (2021)). The SR1.5 and the AR6 WGIII reports show that for such

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temperature targets, carbon dioxide removal is needed. For this, road maps are needed with milestones, explanation of what policies that will be implemented, monitoring and review systems that will be used to assess progress and whether net zero be maintained or if it is a step toward net negative CO_2 emissions. Focus on cumulative CO_2 emissions will be essential for such milestones and it will also need to contain clarifications of how CO_2 removal and/or offset options are included in the net zero target of the Paris Agreement and how the permanence of CO_2 removed (including for offsets) are ensured. In the case of aviation, any continuing emissions of fossil CO_2 beyond around mid-century will require compensating the emissions by permanent removals of CO_2 from the atmosphere.

After the adoption of the Paris Agreement and the publication of the IPCC SR1.5, several concepts concerning balance, net zero, neutrality, and so forth were introduced in discussions and development of climate policies. Due to the complex set of forcing mechanisms involved in the climate impacts the aviation sector does not fit directly with these concepts. The previous sections show that there is a set of issues that need to be addressed to develop a net zero strategy for international aviation that is in line with the ambitions of the Paris Agreement. Some of these issues are of general character and apply to any sector, while some are more specific to aviation.

Whereas we have shown the importance of considering the full range of impacts of aviation on climate change, there are many actors in this field who focus primarily on CO_2, including the international institutions. ICAO's Carbon Neutral Growth Goal—read literally—implies a CO_2 only focus—which could also have implications for a formulation of a net zero goal for international aviation. Much of this is to be achieved by offsetting under the CORSIA scheme, which are largely out of sector avoidance offsets. As such, this does not address a "net zero" requirement for international aviation but rather not increasing emissions over the 2019 baseline. However, in such offsetting, no CO_2 is physically removed from the atmosphere to compensate for the addition of CO_2 to the atmosphere (Allen et al., 2022a). ICAO has now adopted a further goal of net zero carbon by 2050, although it is unclear how this will be met. Furthermore, there is a general ambiguity in the policy discussions with respect to what is meant by "carbon neutral." In many cases this ambiguously covers more than CO_2 only, and there is also a strong discussion around non-CO_2 effects because of its present-day dominance over the sector's CO_2 forcing; however, the "dominance" is the result of strong historical growth of aviation, and the relative fractions are dependent on growth rate of fuel usage (Klöwer et al. (2021)). A comprehensive approach across short-lived climate forcers and long-lived GHGs introduces several challenges. Some of the effects are relatively straightforward "cooling" ones and are not included in our illustrative calculations of temperature responses to various formulations of net zero (Figure 4), but others (net NO_x and contrail-cirrus) have both warming and cooling components, for which we have chosen to include in the net effect in our examples. The effects of the components included in an aggregation of both CO_2 and non-CO_2 components have effects operating on very different time scales; that is, CO_2 has effects on century to millennial time scales and accumulates in the atmosphere, while contrail-cirrus has a lifetime of hours. Thus, placing these effects on a common "equivalent CO_2" scale is hampered by serious limitations, and as pointed out many times in the literature, a "single basket" approach using the aggregate CO_2-equivalent emissions is difficult given the large span in timescales on which the effects operate. Furthermore, inclusion of non-CO_2 effects from aviation is hampered by large and so far, inescapable uncertainties, and there are serious challenges to calculation of effects occurring many decades from now—with a different atmosphere—and potentially different fuel types. The aggregate calculated CO_2-equivalent emissions depend strongly on the chosen metric and time horizon (see Figure 3). The choice of metric can lead to a factor four difference in the CO_2-equivalent emissions needed to counterbalance emissions from aviation. These CO_2-equivalent emission numbers imply very different amounts of CO_2 removals that would be needed to achieve net zero emissions and consequently, different temperature change outcomes. Furthermore, the uncertainties are large and strongly dominated by non-CO_2 effects.

An aggregate metric approach across the forcing components introduces risks of failed mitigation strategies, since the different metrics and time horizons imply different levels of emphasis on CO_2 versus non-CO_2. Mitigation strategies that focus on non-CO_2 (over CO_2) can also come at the risk of increasing CO_2 for, for example, NO_x mitigation (Freeman et al., 2018) or for contrail avoidance (Jaramillo et al., 2022). This then invokes the additional difficulty of evaluating the net outcome between increased CO_2 and decreased CO_2-equivalent emissions and the uncertainties that arise. Moreover, the potential gain of including the non-CO_2 effects in mitigation strategies for aviation in terms of reduced warming should also be weighted against the uncertainties and risk of using incorrect estimates of the underlying effective radiative forcing estimates, which propagate into the emission metric values. This has the potential of resulting in ineffective and potentially costly mitigation efforts, which, at worst, could also have unintended perverse outcomes. In contrast, utilizing SAF to target CO_2 mitigation, can have non-CO_2 co-benefits, in terms of potentially reducing contrails (Burkhardt et al., 2018; Voigt et al., 2021) although the magnitude of the benefit also has large uncertainties.

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Sticking closely to the phrasing of the Paris Agreement Article 4.1 (i.e., "greenhouse gases") supports a CO_2 focus. This implies no inclusion of contrail-cirrus while the gases H_2O and NO_x could be included. Accounting for the indirect effects of NO_x on tropospheric ozone and methane would be consistent with the indirect effects of CH_4 included in GWP for this gas—and hence in current policy making across other sectors. While there are arguments against including the full set of warming components in a net zero concept for aviation, one should also keep in mind that the intention of Article 4.1 is to limit human induced warming, that is, to support the achievement of Article 2. Different interpretations of the Paris Agreement goals are possible (e.g., Mace (2016), Schleussner et al. (2016), Rajamani and Werksman (2018), Allen et al. (2022a), Schleussner et al. (2022)). The global temperature goal to which a net zero goal for aviation is meant to contribute needs to be made explicit; that is, clarity is needed regarding whether the "balance" contributes to temperature stabilization or declining temperatures.

Furthermore, updated and more detailed scenarios could significantly strengthen the basis for assessments of the role of this sector in the context of the Paris Agreement. Scenarios are used as a main tool for assessment of possible futures and for the paths toward net zero emissions. But as pointed out and shown in our illustrative calculations, there are limited available scenarios for the aviation sector and those that exist give insufficient basis for studies of possible future impacts and pathways to net zero for aviation. In particular, while some studies have explored various scenarios (Bier & Burkhardt, 2019; Dray et al., 2022; Grewe et al., 2021; Klöwer et al., 2021) more realistic scenarios in the SSP-RCP framework (O'Neill et al., 2020) accounting for how new types of fuels will affect not only CO_2 but also the non-CO_2 components are needed.

There is a risk of increased warming from non-CO_2 components, under assumptions of increased growth of the sector. Depending on implemented policies and measures such as new technology, fuel (e.g., low-aromatic content "sustainable aviation fuels," LH_2), routing, and so forth, forcing from contrail-cirrus may change significantly in the future. But in the case of unchanged levels of contrail-cirrus forcing per unit fuel (i.e., continued use of fossil kerosene), then one could end up in a situation where CO_2 is compensated by removals while the warming effects of non-CO_2 components continue unabated—which would be growth dependent, that is, roughly linearly related to the fuel usage. This would not be in support of the temperature ambition stated in Article 2 of the Paris Agreement.

How to formulate and implement a net zero goal for aviation must rest on solid scientific understanding of the effects of the candidate components for inclusion. Policymakers and the aviation sector need to be aware of the issues discussed in this article and determine how the aviation sector most effectively can contribute to the goals of the Paris Agreement.

AUTHOR CONTRIBUTIONS

Jan Fuglestvedt: Conceptualization (lead); funding acquisition (equal); investigation (equal); methodology (equal); project administration (lead); supervision (lead); visualization (equal); writing – original draft (lead); writing – review and editing (lead). **Marianne T. Lund:** Conceptualization (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Steffen Kallbekken:** Funding acquisition (equal); investigation (equal); writing – original draft (equal); writing – review and editing (equal). **Bjørn Hallvard Samset:** Formal analysis (equal); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). **David S. Lee:** Conceptualization (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

We have used scenario emission data from the IIASA SSP database and the data underlying the illustrative figures will be made avilable upon request.

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ENDNOTES

[1] https://climatechampions.unfccc.int/join-the-race/

[2] Note that scientific analyses tend to focus on the aviation "sector," rather than making what is essentially a policy discrimination of international and domestic aviation. Both aspects are dealt with in this article.

[3] https://climateactiontracker.org/sectors/aviation/targets/

[4] https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035

[5] https://www.icao.int/environmental-protection/Documents/Assembly/Resolution_A40-18_Climate_Change.pdf

[6] CORSIA has a pilot phase (2021–2023), a "first phase" (2024–2026) and a "second phase" (2027–2035). The pilot and first phases are voluntary whereas the second phase applies to all ICAO Member States (https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-FAQs.aspx)

[7] https://www.icao.int/environmental-protection/LTAG/Pages/LTAGreport.aspx

[8] https://www.icao.int/Meetings/a41/Documents/Resolutions/a41_res_prov_en.pdf

[9] First Annual Report of the High Council on Climate of France; https://www.hautconseilclimat.fr/wp-content/uploads/2019/09/hcc_rapport_annuel_2019-english.pdf

[10] The AR6 IPCC Glossary did not present any definition of "climate neutrality." This concept was included in the glossary of IPCC SR1.5 and is frequently used in climate policy discussions (often without any clear adopted definition).

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