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Lightweight climate models could be useful for assessing aviation mitigation strategies and moving beyond the CO_2-equivalence metrics debate

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Assessing mitigation strategies for aviation is a critical issue for the aviation stakeholders, while the debate continues on the most appropriate CO_2-equivalence metrics to address non-CO_2 effects. Here, we propose two lightweight climate models that can be parameterised to assess these strategies and move beyond the CO_2-equivalence metrics debate. A first approach relies on the use of the GWP* method, while a second one uses the FaIR climate emulator. These lightweight models, which should be considered as a new family of climate models for aviation that facilitate parametric studies, provide a straightforward and consistent means of evaluating mitigation strategies at the temperature level, although they are still limited for informing policymakers due to the significant uncertainties involved. They bypass the need for CO_2-equivalence metrics for comparing strategies. The latter should rather be used for other applications, such as policy mechanisms to encourage the emergence of strategies, as they are not suitable for assessing temperature changes from aviation. The debate on the choice of CO_2-equivalence metrics could then focus on methodological and ethical criteria. However, this paper demonstrates that the higher the traffic, the more appropriate it is to choose CO_2-equivalence metrics with high values for consistency with temperature estimates.

Aviation contributes to global warming through CO_2 emissions and non-CO_2 effects. The combustion of jet fuel at high altitudes directly impacts the climate by releasing CO_2 and H_2O, which are greenhouse gases, and sulphur dioxide and soot which have a short-term radiative effect. Aviation also has an indirect effect due to the short-lived formation of contrails cirrus, aerosol-cloud interactions, and alterations in O_3, CH_4 and stratospheric water vapour, all three greenhouse gases, caused by NO_x emissions. The various non-CO_2 effects are more complex to assess and therefore more uncertain. The contribution of aviation to climate change can be expressed in terms of Radiative Forcing (RF), or, better still, Effective Radiative Forcing (ERF), which accounts for rapid atmospheric responses to a given climate forcing. In 2018, aviation CO_2 emissions represented 1.3% of the total anthropogenic ERF, while the aviation total effects of aviation's CO_2 and non-CO_2 components contributed to 3.5%[1].

The possibility of reducing aviation climate impact and the associated levers of action have been discussed thoroughly in the literature[2]. Key technological levers include improving aircraft efficiency – both in terms of design and operational practices – and adopting decarbonization measures, such as the use of low-carbon alternative fuels[2]. Regarding operational strategies, a proposal to reduce contrail formation involves making minor adjustments to flight altitude, based on actual weather conditions, to avoid flying through regions of ice supersaturation[3]. More generally, shifting the fleet average cruise altitude to lower altitudes allows a reduction of the climate impact[4,5]. Indeed, the radiative forcing from net NO_x, H_2O and contrails decreases at lower cruise altitudes. Another possible option to mitigate the climate impact of contrails is to reduce airborne soot emissions by using cleaner burning alternative fuels or by decreasing the aromatic content of fossil fuel[6,7]. Alternative fuels, such as biofuels or electrofuels, can also limit CO_2 emissions on the whole life cycle and do not emit SO_2 as their sulphur concentration is zero. However, taking account of these different levers of action in prospective scenarios is still relatively complex, due to the small number of models available and the significant uncertainties that remain. Aviation's future climate impact depends for instance on decisions related to aircraft development, fuel usage, and new operations. Therefore,

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to choose the best path toward achieving environmentally-friendly aviation, it is essential to study and compare the climate impact of net-zero initiatives across various potential future scenarios.

Quantifying the RF and ERF of non-CO_2 effects is much more challenging than for CO_2 and remains a subject of scientific debates. Important uncertainties remain[8], especially, for contrails, which have been particularly explored during COVID-19[9–12] with contrasted conclusions, and for NO_x emissions, due to the complexity of modelling[13–15]. Estimates are still few and far between for aerosol-cloud interactions[1,16,17], with some authors giving a significant positive or negative radiative forcing, comparable to major contributors such as CO_2 and contrails. One of the main reasons for explaining these uncertainties is the short lifetime of non-CO_2 emissions. Moreover, the effects of non-CO_2 emissions on the chemical composition of the atmosphere and on aviation-induced cloudiness largely depend on conditions that vary significantly with flight altitude, geographical area, emission time, lifetime, fuel type and background concentrations, among others. For instance, the net radiative forcing of aviation NO_x emissions depends on which gas predominates, and this depends on emissions from all sources and thus the background concentrations versus time[14,18]. NO_x emissions lead to the short-term formation of ozone (O_3-short) (a warming) and the long-term destruction of ambient methane (CH_4) through hydroxyl (OH) production (a cooling). Reducing methane results in a long-term reduction of O_3 (a cooling) and a long-term reduction of H_2O in the stratosphere (a cooling) due to reduced methane oxidation. O_3 is a chemically reactive gas with a relatively short lifetime of 1 to 3 months in the troposphere, whereas the radiative forcing of CH_4 exponentially declines with a perturbation lifetime of about 12 years[19]. Similarly, the climate impact of persistent contrails and cirrus clouds induced by contrails depends on their lifetime, time of day, coverage, optical thickness, temperature, Earth's albedo and other environmental conditions. In ice supersaturated areas, the lifetime can be long, sometimes exceeding 17 hours, and contrails can significantly contribute to cloud coverage[20].

The understanding of non-CO_2 effects has improved over the years[1,21], enabling the characterisation of the relationships between the atmospheric emissions of Short-Lived Climate Forcers (SLCFs) and the increase in radiative forcing within acceptable confidence intervals[22]. What's more, the contribution of these different mechanisms, and in particular the non-CO_2 effects, can also be assessed in terms of their contribution to temperature rise.

Three main approaches can be used for estimating the temperature increase induced by aviation. First, 4D climate models like Earth System Models (ESM) can be used for estimating the temperature increase. It allows accurate and local modelling, but at the cost of a complex usage and long calculation times. To the best of our knowledge, no 4D ESMs that include specific modelling of aviation non-CO_2 effects are available in open access. Simplified frameworks including or dedicated to aviation, such as AirClim[23] (a linearisation of the E39/C climate-chemistry model[24]) and APMT-IC[25], are for instance used respectively in refs. 26,27. Second, the temperature can be obtained using 0D climate models, also called emulators, such as MAGICC[28], CICERO-SCM[29], OSCAR[30], or FaIR[31]. These climate models integrate for instance carbon and methane cycle modelling and allow accurate estimations based on emissions or ERF. They are for instance used in refs. 32–35. However, they cannot model the geographical dependence of the radiative impact of some species, and do not always have specific modules for the non-CO_2 effects of aviation. Lastly, in a simplified approach, the temperature can be estimated by multiplying the Transient Climate Response to cumulative carbon Emissions (TCRE) coefficient by cumulative equivalent emissions. These equivalent emissions can be obtained from the ERF values using dedicated climate metrics, such as GWP*[36] or LWE[37]. This method, for instance used in refs. 22,38,39, is relatively simple to use and allows short calculation times. However, it may be limited in its ability to reproduce complex temperature profiles, particularly for sudden changes in emissions. The choice of the climate metric is crucial and conventional CO_2-equivalence metrics are for instance not appropriate in this context[40]. Indeed, the latter, used to compare a species with CO_2 emissions over a certain time horizon, treat SLCFs, such as aviation non-CO_2 effects, as 'stock' pollutants, whereas the change in SLCFs emission rates is necessary to assess their temperature response, in particular when SLCFs emissions are stable or declining.

The previous analysis of the scientific literature highlights significant gaps in current methods for assessing aviation-related climate strategies. Firstly, there is an urgent need to have access to reduced complexity climate models specifically tailored for aviation, allowing for extensive simulations and the ability to modify various climate parameters related to both Earth system processes and aviation-specific factors. Additionally, it is crucial to develop models that enable the incorporation of various mitigation strategies, particularly those targeting non-CO_2 effects. Finally, it is important to have open-source models that would facilitate broader dissemination and continuous improvement by the scientific community. All these observations motivate the development and use of lightweight climate models for aviation.

The current study aims to address these needs by providing open-source climate models that allow the calculation of aviation's contribution to global warming across different future scenarios, while accounting for various mitigation strategies. Another objective is for the model to easily accommodate uncertainties, meaning that it can yield results based on different climate parameterisations and evolve alongside scientific advancements, for a better understanding of aviation non-CO_2 effects. This research also aims to show that the use of CO_2-equivalence metrics, for which the choice is a complex debate, can be replaced by these models for certain applications.

Here, we present two modelling approaches for aviation's climate impact, encompassing both CO_2 and non-CO_2 effects. These approaches enable the calculation of temperature change through lightweight and innovative methods, using ERF estimates in the two cases. The term "lightweight" is used here to refer to models of reduced complexity, allowing quick and easy execution. The detailed description of these methods, settings and calibrations is provided in the "Methods" section at the end of the paper.

On the one hand, the first approach relies on the use of the GWP* method to estimate warming equivalent emissions, coupled with the use of the TCRE climate coefficient to estimate temperature change. Three settings for the GWP* method are studied in this paper:

- settings from Lee et al.[1] based on simple methane models (named Lee et al. settings in the following),
- updated settings based on improved methane models and very short lifetimes for non-CO_2 effects (named *updated settings* in the following),
- updated and improved settings based on improved methane models and calibrated lifetimes for non-CO_2 effects (named *selected settings* in the following).

The last settings, which rely on the use of an original calibration based on the use of other climate models, are selected as a reference method for GWP* in this paper.

On the other hand, the second approach relies on the use of an open-source climate emulator, here FaIR. This climate emulator was chosen due to its open-source availability and its widespread use, for instance in IPCC Sixth Assessment Report[41]. FaIR also includes dedicated methods for integrating aviation climate impacts such as contrails. Some adaptations have been performed to take into account the different non-CO_2 effects, including, in particular, equivalent emissions calculated with GWP* for methane decrease due to NO_x emissions.

This paper explores the performance of these lightweight climate models for aviation, by validating the models, understanding their advantages and limitations in different cases of application, and highlighting the prospects they open up in terms of research and public policy. In particular, we demonstrate the possibility of evaluating mitigation scenarios and discuss the implications for the debate on CO_2-equivalence metrics. For that, these models are integrated (directly through equations for GWP* and through the open-source module for FaIR) into AeroMAPS, an open-source

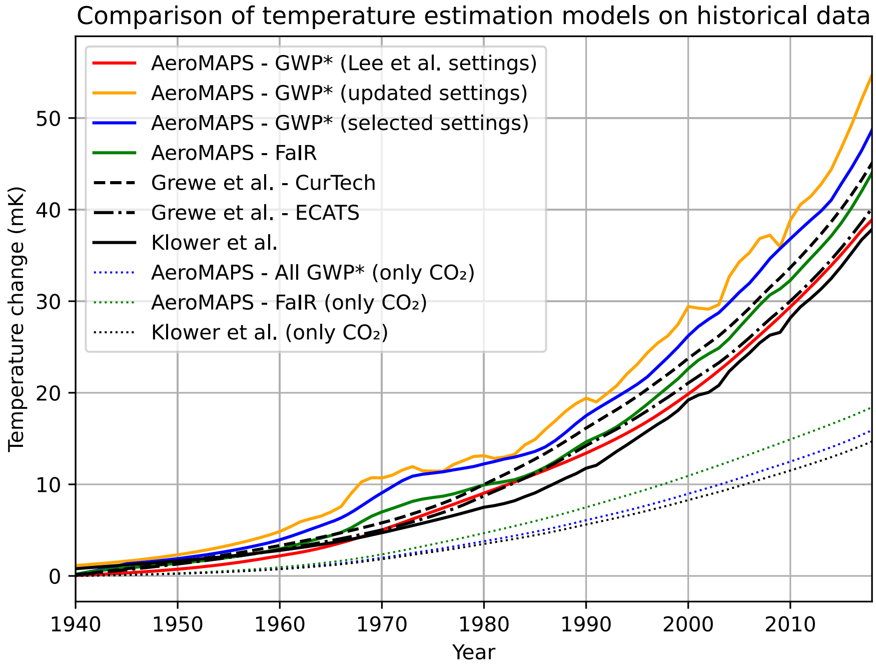


Fig. 1 | Historical contribution of aviation to surface temperature change estimated by different models and settings. The different AeroMAPS models, based on the GWP* method (for each of the three different settings described above) or the FaIR one, are shown in colour and can be compared with reference models shown in black, such as the AirClim model from Grewe et al.[23] (for two different settings), and the model from Klöwer et al.[39]. The contribution of aviation CO_2 emissions is shown as dotted lines.

framework for performing multidisciplinary assessments of prospective scenarios for air transport[42]. AeroMAPS has also been updated with new models for taking into account several levers of action dedicated to non-CO_2 effects mitigation.

In the following, the proposed climate models are validated using historical and reference data. Several applications and sensitivity analyses using AeroMAPS are then provided for highlighting the advantages and limits of these lightweight models. Lastly, a discussion is provided concerning their applications in terms of scientific research and public policies. All the methods used in this paper (AeroMAPS, non-CO_2 mitigation, and climate models) are described in the "Methods" section at the end of the paper.

Results

Model comparison and validation

The two lightweight models studied in this paper, with the three different settings for the GWP* approach, are compared and validated in this section. For that, comparisons with models from the literature are performed using historical data. Moreover, several test cases are proposed for evaluating the response to a variety of emissions profiles (long-term growth, long-term decline, stabilisation, sudden halt).

First, an initial validation of the two proposed methods is provided in this section. This validation is based on a comparison with two reference models from the literature. On the one hand, the non-linear climate-chemistry response model AirClim[23,26] is used. AirClim takes into account variations in the concentrations of CO_2, water vapour, ozone, methane, and the formation of contrail-cirrus. It also considers their lifetimes, impacts on the Earth's radiation budget, and eventual alterations in near-surface temperatures. Two different scenarios, corresponding to different settings, are included. On the other hand, another model from Klöwer et al.[39] is also used. It represents a simplified approach for estimating temperature response, through the use of Linear Warming Equivalent CO_2 emissions.

Figure 1 shows the resulting estimates in terms of surface temperature change attributable to aviation from 1940 to 2018 for the reference models and the models considered in this paper. The latter rely on historical data and median sensitivities to emissions from refs. 1,39, and are indicated as follows: AeroMAPS - Method (settings).

Regarding the historical evolution of aviation's contribution to temperature change, including non-CO_2 effects, all methods exhibit consistent trends with each other. The FaIR method proposed in this paper shows very similar values to those obtained from AirClim. Similarly, the GWP* method using Lee et al. settings closely resembles AirClim-ECATS and also aligns with Klöwer et al. However, for the GWP* method using updated and selected settings, higher temperature increases are found. This is due to the shorter lifetimes chosen for certain species, such as ozone-short or contrails: 1 year for the updated settings, and 6 years for the selected ones (see "Methods" section). As a consequence, the temperature rises more quickly when there is an important increase in air traffic (and therefore in contrails). In the case of the updated settings, due to very short lifetimes, the temperature can fall when there is a decrease in air traffic, as in 2001 and 2009. The GWP* method with the updated settings diverges significantly in absolute values, whereas a limited difference is found with the selected settings. Indeed, according to the GWP* method with updated settings, in 2019, aviation's contribution is nearly 10 mK higher than the estimate provided by AirClim-ECATS and nearly 17 mK higher compared to Klöwer et al., i.e. a difference of between 22 and 45%. For the selected settings, the difference is limited between 9 and 29%.

The small or limited differences between the models are explained by several factors. First, the historical emissions used are not the same for the different papers. Whereas AirClim data are not specified, the scope differs between AeroMAPS data and the ones from Klöwer et al. For instance, AeroMAPS does not take into account military emissions, but does include emissions from the fuel production process. A modification of AeroMAPS scope data allows obtaining closer results. Then, the sensitivities to emissions for aviation non-CO_2 effects differ. Indeed, whereas they are similar for AeroMAPS and Klöwer et al. model, the ones from AirClim are not available and are probably different. Lastly, the remaining differences are explained by the models themselves. For instance, some methods rely on simplified climate metrics (e.g. AeroMAPS - GWP* and Klöwer et al. model), while others rely on more conventional climate models (e.g. AeroMAPS - FaIR and Grewe et al. model) which have different calibrations.

Focusing on CO_2 emissions alone, a slight difference between the GWP* method and the one used in Klöwer et al. is observed. This discrepancy is entirely due to the above-mentioned variations in historical data, as the underlying calculation of temperature increase remains the same in both methods for CO_2 emissions, with a TCRE set at 0.45 $^{\circ}C/1000GtCO_2$. However, the method based on the use of FaIR yields higher results. Notably, this model incorporates considerations of the carbon cycle and background emissions, resulting in a different value for the equivalent to the TCRE

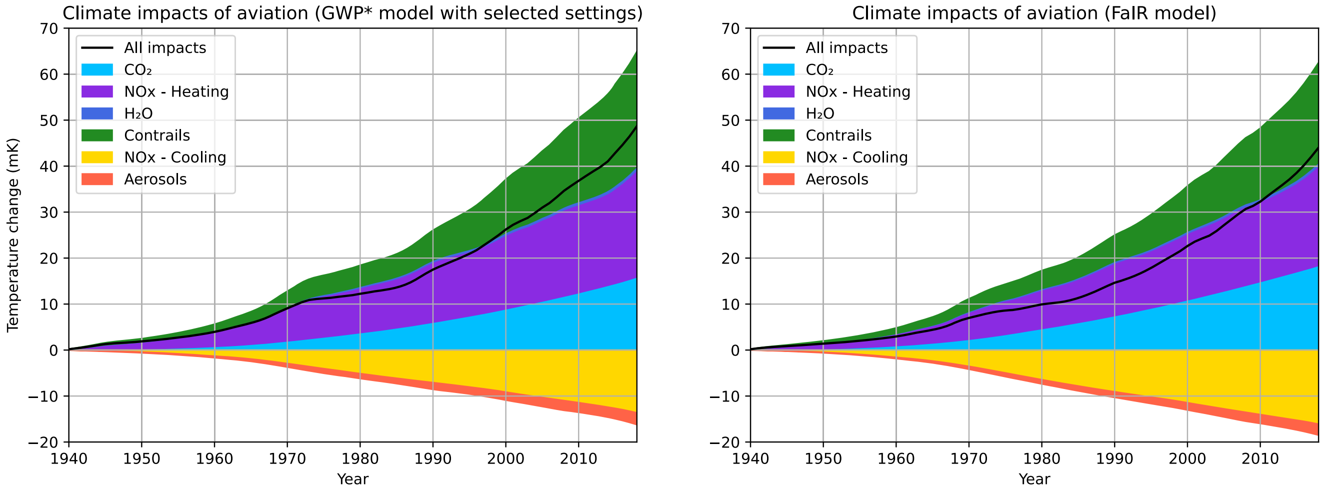


Fig. 2 | Individual contributions of aviation-emitted species to surface temperature change from 1940 to 2020 for the AeroMAPS models. The figure on the left shows the results using the GWP* approach (with selected settings) and the figure on the right shows the results using the FaIR approach.

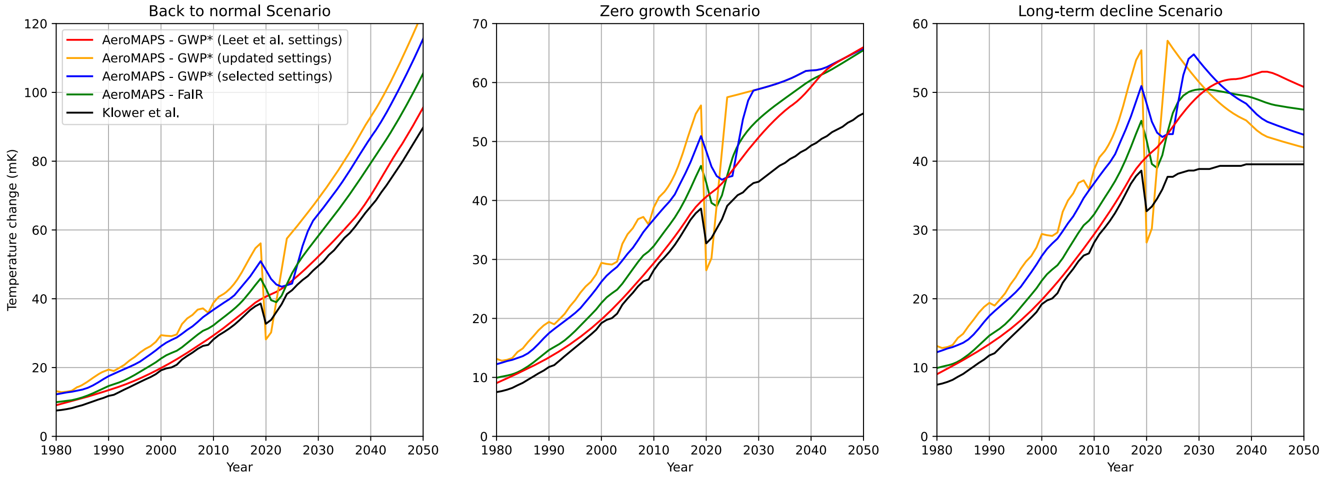


Fig. 3 | Contribution of aviation to surface temperature change until 2050 according to different methods. Each methods simulates three prospective scenarios from Klöwer et al.[39]: Back to normal, Zero long-term growth, and Long-term decline.

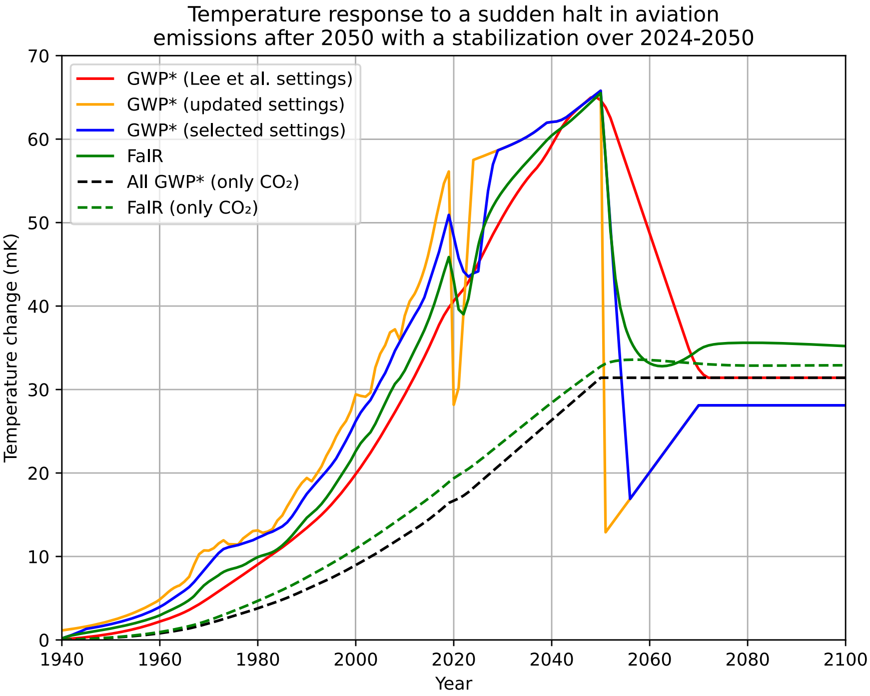
(0.53 °C/1000GtCO$_2$ here). In fact, the uncertainty associated with climate response makes it intricate to determine accurately the absolute temperature value with precision.

Figure 2 illustrates surface temperature change attributed to historical aviation emissions, this time presenting the individual contribution of each species, calculated by GWP* (with the selected settings) and FaIR methods. As long as the evolution of emissions occurs gradually, the temperature response of each species appears very similar across both methods, with only some minor discrepancies and a slightly faster rate for GWP*. The cooling effect of NO$_x$ emissions, resulting from methane and ozone depletion, is slightly weaker with the GWP* method, in contrast to the warming effect of NO$_x$ emissions, which appears to be larger compared to the estimates derived from the FaIR model. This leads to a greater NO$_x$ contribution according to GWP*. A notable difference is observed in contrails, where GWP* indicates a larger impact. Overall, short-term effects are accentuated by GWP* due to its calibration as mentioned above.

In order to validate the models more widely, various test cases are considered in the following. A first analysis is based on the study of different prospective scenarios produced by Klöwer et al.[39], whose historical results were discussed above. Three radically different scenarios are studied: a first scenario assuming a post-COVID-19 recovery period from 2021 to 2024, followed by continued emission growth at a rate of 3%, another scenario with 0% emission growth after 2024, meaning emissions remain constant from that point onward, and a last scenario showing a long-term decline of 2.5% in emissions. These assumptions have been used to reproduce the scenarios with AeroMAPS. From a qualitative point of view, different results are expected. When emissions are stabilised (0% growth), the contribution of non-CO$_2$ emissions remains constant, while warming due to CO$_2$ emissions continues to grow as CO$_2$ continues to accumulate. This highlights a clear distinction between the CO$_2$ and non-CO$_2$ effects. Indeed, to stabilise the warming due to CO$_2$, emissions would need to be stopped, not just their growth[40]. Figure 3 shows the different results in terms of surface temperature response.

As a first step, it is important to comment on the response to COVID-19. The GWP* method with the updated settings triggers an immediate system response, whereas the GWP* with Lee et al. settings reacts very weakly over the long term. The extremely rapid change in temperature with the GWP* method with the updated settings is due to the fact that this model is calibrated with very low time parameters to represent the very short lifetimes of non-CO$_2$ effects, and in particular contrails (see “Methods” section). The GWP* method with the selected settings and the FaIR method exhibit an intermediate but similar response, which can be explained by the way the selected settings have been chosen (see “Methods” section). In fact, the temperature response lags behind the forcing, as it has a non-instantaneous temporal reaction. The climate model reproduces the temporal evolution of temperature

Fig. 4 | Contribution of aviation to surface temperature change until 2100 in the case of a sudden halt in aviation emissions in 2050 according to the different AeroMAPS models. The simulation includes COVID-19 over 2020–2024 and constant emissions over 2024–2050. The contribution of aviation CO_2 emissions is shown as dashed lines.



caused by a one-year emission pulse, with the cumulative effect of all yearly emission responses determining the actual temperature change. This temporal response feature of temperature depends on the settings of the GWP* method.

As a second step, the differences between the models can be analysed for each scenario. In the initial theoretical scenario (“Back to normal”), all methods and settings exhibit a very similar behaviour, the discrepancy having been explained previously in the historical validation. In the second scenario (“Zero growth”), the temperature response with GWP* choosing updated and selected settings stabilises faster than with the three other methods, which exhibit a more significant slope for approximately 20 years after aviation growth has ceased. Significant contrast emerges when emissions start to decline (“Long-term decline”). FaIR reveals a more gradual reduction in climate impact, progressively developing over time. In contrast, this decrease seems quicker and stronger with the GWP* method, except for Lee et al. settings which induce a time lag as observed for COVID-19. In general, we can observe that Klöwer et al.’s results exhibit a similar temporal response to the FaIR method. However, when air traffic declines, Klöwer et al. show stabilisation for the next 25 years instead of a decrease in climate impact, as supported by the other methods of this paper.

A second analysis focuses on a sudden halt of aviation emissions, the initial insights for which were provided by studying the response of models to COVID-19. Although it may seem improbable, exploring such scenarios can offer valuable understanding of the model’s behaviour. However, there are very few studies[5] in which such scenarios have been investigated. Figure 4 illustrates the aviation’s contribution to temperature change, calculated using the different climate models developed for AeroMAPS, in a scenario where there are no further aviation emissions from 2050, after a stabilisation over 2024–2050. The GWP* method with Lee et al. settings reacts gradually over 20 years, while with the other two settings, the reaction is more immediate. FaIR reacts immediately but evolves gradually, which seems closer to the results obtained by Frömming et al.[5] with AirClim. The GWP* method with the updated and selected settings, in addition to FaIR although in a much more discrete manner, have a drop just when emissions are ceased. The drop recovers after 20 years, consistent with the lifetime of methane. The temperature profile, with an increase in temperature after a few years, can be explained by the fact that non-CO_2 species with a warming effect have shorter lifetimes than those with a cooling effect due to methane decrease. In such scenarios, we can observe the limitations of GWP*: while it can reproduce scenarios with a gradual evolution, it does not reproduce abrupt situations as accurately due to its artificial representation of temperature response inertia.

As a consequence, the previous analyses enable us to assess the performance of the models in different situations. In terms of historical analyses, all the models tested give results that are consistent with the state of the art. The various case studies allow testing the limits of the models, and more specifically of the settings for the GWP* approach, particularly in the event of sudden variations in emissions. This shows that the FaIR approach is the most appropriate model, and that the GWP* approach with the selected settings also provides consistent results. Concerning the FaIR approach, similar results would probably be obtained with other climate emulators, such as those mentioned in the introduction. In the rest of the paper, only the FaIR approach, and occasionally the GWP* approach with the selected settings, are used due to their better performance.

The models studied previously are used in the following for exploring the climate impacts of mitigation scenarios for air transport. First, several illustrative scenarios are presented and analysed. Then, sensitivity analyses are performed on ERF uncertainties for contrails and NO_x. The scenarios are also classified based on their temperature response. Finally, several CO_2-equivalence metrics are used and compared using the previous scenarios.

Application to mitigation scenarios

As mentioned in the introduction, to meet its greenhouse gas emissions reduction targets, the aviation industry urgently needs to implement necessary actions and make decisions that account for long-term consequences. Thus, it is crucial to compare the proposed mitigation strategies while taking into account not only CO_2 emissions but also non-CO_2 effects and their associated uncertainties. The majority of efforts to mitigate the climate impact of aviation focus on CO_2 reduction strategies. Among these, the development of alternative energy carriers, including in particular hydrogen and drop-in fuels suitable for existing aircraft such as biofuel and electrofuels, emerges as a key measure. Indeed, according to a study on international aviation from the International Civil Aviation Organization (ICAO)[43], drop-in fuels could potentially enable a reduction between 15% and 55% of CO_2 emissions by 2050 compared to 2019 levels. However, even if alternative energy carriers could also affect non-CO_2 effects, reducing these effects continues to pose a challenge. Several projects are currently

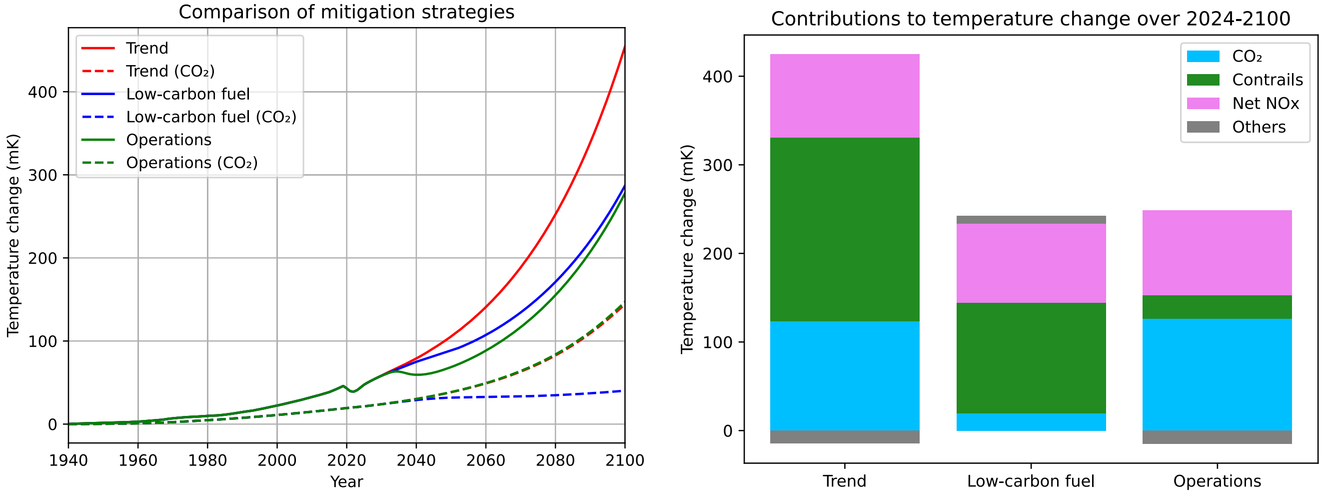


Fig. 5 | Aviation's contribution to surface temperature change from 1940 until 2100 across three future scenarios with 3% aviation growth. 1/ Trend (exclusive use of kerosene), 2/ Low-carbon fuel (adoption of low-carbon fuels by 2050), 3/ Operations (deployment of contrail avoidance measures achieved by 2040). The bars show the temperature change in 2100 relative to 2024 for each scenario. "Others" corresponds to H_2O, sulphur dioxide and soot emissions.

underway to develop innovative solutions aimed at reducing their impact on flight operations. Contrail avoidance stands out as one of the most promising solutions that the aviation industry aims to implement in the near future. Avoiding flying in specific regions is part of the strategies that could help limit the formation of persistent contrails and minimise aviation's impact on the climate. However, these operational strategies could lead to fuel overconsumption. As a consequence, climate trade-offs need to be considered when looking at these strategies in detail.

In this section, three illustrative scenarios are considered in order to highlight the possible uses and results of these lightweight climate models in the context of aviation prospective studies. In addition to a baseline scenario, two mitigation ones are considered: one is based on the use of low-carbon fuels, while the other relies on the deployment of contrail avoidance strategies. These scenarios are simulated with AeroMAPS, and their climate impacts are evaluated using the FaIR method. Analyses at the temperature level facilitate the comparison of the short and long-term impacts.

For all the scenarios, the future air traffic growth is fixed at 3% per year, according to current forecasts used by the Air Transport Action Group (ATAG)[44]. For reasons of simplicity, efficiency gains are not included in this study. The first mitigation scenario assumes 100% low-carbon aviation fuels by 2050, 50% biofuel and 50% electrofuel, with a gradual implementation starting from 2030. Life-cycle emissions, from biofuel (using Fischer-Tropsch pathway from residues) and electrofuel production (using dedicated renewable electricity considering a emission factor of 10 gCO_2/kWh), are considered, leading to CO_2 emission reduction greater than 90%. Note that this value is optimistic, mainly because of the limited availability of biomass feedstock and dedicated renewable electricity. The second mitigation scenario keeps using exclusively fossil fuel, but shows the effect of avoiding 80% of contrails by 2040, starting the implementation of operational measures in 2030, and considering a 2% fleet-level overconsumption caused by modifying the flight plans in order to avoid persistent contrail formation regions. This hypothesis is an arbitrary target derived from the Pareto front of avoided contrails versus overconsumptions, proposed by Matthes et al.[45], keeping in mind that the feasibility of successful deployment of contrails mitigation measures at global scale, and the efficiency of such schemes, still remain to be proven. Note that lower values of overconsumption at fleet level are usually considered, but using this value makes it easier to understand the resulting phenomena.

Figure 5 compares surface temperature change for the baseline scenario and the two mitigation ones. Results are represented from 1940 to 2100 in order to provide a sufficiently long period to appreciate the changes and draw conclusions about the measures taken.

Concerning the first mitigation scenario based on the use of low-carbon fuels, the temperature increase due to aviation CO_2 emissions is almost stable after 2050. Additionally, we notice a decrease in the impact of contrails, as the model incorporates the impact of using low-aromatic fuel on reducing contrail cloudiness, even though the underlying benefit on contrails forcing still needs to be confirmed. In addition, deploying low-carbon synthetic fuels also has a smaller adverse warming effect because the considered low-carbon fuels do not emit sulphur particles, which have a cooling effect. Finally, the net effect on non-CO_2 remains positive over the period 2024–2100, which corresponds to a temperature increase.

For the second mitigation scenario relying on contrail avoidance strategies, the temperature impact of non-CO_2 emissions decreases significantly and rapidly, resulting in a reduced overall contribution from aviation, even lower than in the previous mitigation scenario, as temperature reacts quickly to the decrease in contrails radiative forcing. However, CO_2 emissions are still increasing a lot, and their influence continues to grow. The additional consumption due to contrails avoidance has a moderate CO_2 effect compared to the baseline scenario. Nevertheless, it's important to acknowledge that this contribution accumulates and persists over time.

Sensitivity to ERF uncertainties

On top of uncertainties associated with the selected models for deducing aviation's contribution to climate change, there are additional uncertainties that require careful consideration. Therefore, in this section, specific analyses are provided concerning the ERF uncertainties for two non-CO_2 effects: contrails and NO_x emissions. It allows to analyse how these uncertainties may affect the results, aiming to understand their implications for decision-making and to identify necessary research pathways for enhancing model predictions.

The global annual mean ERF attributable to contrail cirrus in Lee et al.[1] is estimated at 57.4(17, 98) mW/m^2 for 2018. This value is higher to that of aviation's cumulative CO_2 emissions, with differing implications for climate change, and yet it is a highly uncertain component.

Figure 6 aims to illustrate how these uncertainties affect the previously studied mitigation scenarios, for instance the one with contrail avoidance operations, i.e., whether implementing these operations would lead to a significant decrease in aviation contribution considering the possible values of contrails ERF.

The figure on the left of Fig. 6 corresponds to the figure on the left of Fig. 5 incorporating uncertainty intervals associated with Lee et al.'s contrails ERF. The uncertainty interval widens as aviation's contribution to temperature change increases, so when contrails ERF is reduced by 80%, the interval also decreases. It is interesting to discuss the extreme values within

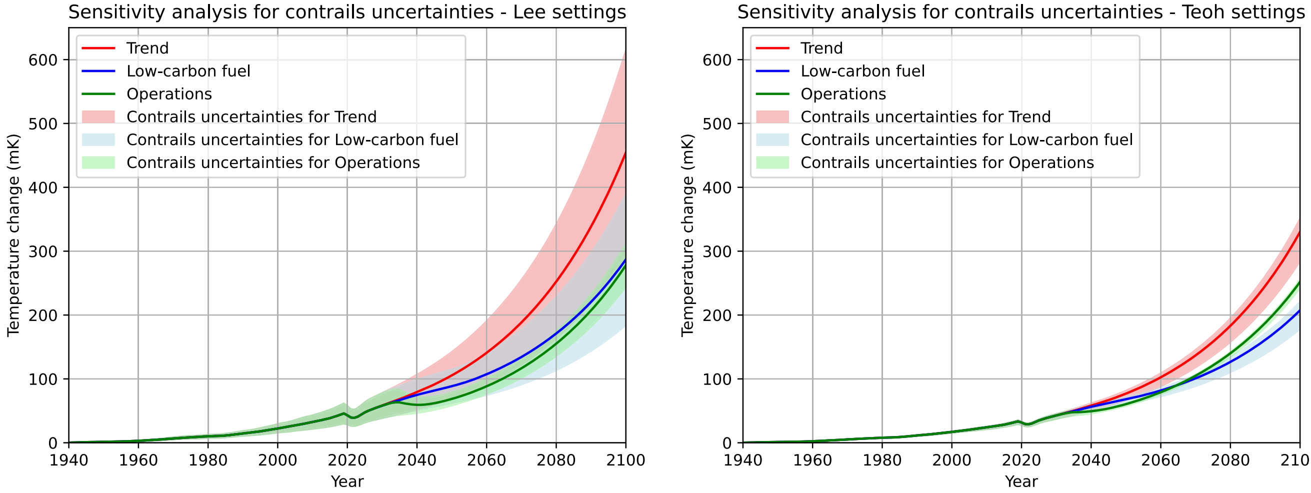


Fig. 6 | Climate impact of aviation for the scenarios depicted in Fig. 5 integrating contrails uncertainties. The figure on the left shows the results with Lee et al.[1] settings and the figure on the right shows the results with Teoh et al.[46] settings (with a lower mean estimate). Scenarios from Fig. 5 are reused and the uncertainty ranges are shown.

the uncertainty range. Focusing on the warming in 2100 and considering the minimum value of ERF, aviation's contribution would be reduced by around 50 mK thanks to contrail avoidance. This reduction accounts for 17% of aviation's climate impact. However, if we consider the maximum ERF value, the difference would be more than 300 mK, meaning a 49% reduction.

Alternative values of the contrails ERF can be considered, for instance by using recent estimates from Teoh et al.[46]. They have simulated the global contrail climate forcing, obtaining a global annual mean contrail net RF of 62.1(34.8, 74.8) mW/m^2 in 2019, which translates into an ERF of 26.1(14.6, 31.4) mW/m^2 in 2019 using the ERF/RF values from Lee et al. This is 44% lower than current best estimates for 2018 with a smaller range of uncertainty. The results from Teoh et al. are highlighting a downward trend in the impact of contrails from aviation, observed as well in recent publications such as[9,11], even if others such as Gettelman et al.[10] are confirming a most probable radiative forcing value close to the assessment by Lee et al. Specific studies also go in the direction of a lower contrail climate forcing, due to a lower contrail efficacy[47,48]. These efficacy values could eventually be used to estimate ERF/RF ratios, although methodological problems remain[49].

The figure on the right of Fig. 6 shows the results for the three scenarios re-simulated using these alternative estimates. It shows that, by 2100 and for best estimates, aviation's temperature impact is lower by around 30% in the case of the trend scenario. It is interesting to note that, in this case, the scenario using low-carbon fuels induces a lower temperature increase than the one based on contrails avoidance.

Lee et al. provide an ERF sensitivity to emissions of 5.5 ± 8.1 mW/m^2/TgN for aviation net NO$_x$[1]. The significant range of uncertainty yields the possibility of negative values, meaning the net NO$_x$ effect may be cooling. The posterior study of Skowron et al.[14] presents new RF computations for all NO$_x$ species for a future (2050) range of Representative Concentration Pathways (RCP) scenarios together with ICAO-CAEP aviation emission projections. It provides figures for two alternate parametrisations of CH$_4$ forcing, which acts both on the methane depletion and the long-term ozone cooling impacts caused by NO$_x$. Since we are looking at future prospective scenarios, we consider for our model the RF sensitivities to emissions given in Skowron et al.[14] for the year 2050, for the "Low NO$_x$ High Tech" scenario with RCP4.5 background. Interestingly, while this alternate net NO$_x$ sensitivity to emissions expressed in RF is slightly negative (cooling) at -1.0 mW/m^2/TgN, when converted to ERF with the ERF/RF ratios per species from Lee et al., it becomes positive (warming) at 2.6 mW/m^2/TgN as shown in Table 1, yet still significantly lower than the best value from Lee et al. This underscores the sensitivity of the net NO$_x$ effect, derived by summing positive and negative terms of the same order, to changes in sign depending on uncertainties in some terms, on the background emission scenario and even on the metric considered. A similar observation is also reported in ref. 15, in which the future aviation net NO$_x$ RF is assessed as cooling, but becomes warming when converted to ERF with the same ratios from Lee et al.

Table 1 | RF and ERF sensitivities to emissions for NO$_x$ species, in mW/m^2/TgN

NO$_x$	Default: Lee et al.		Alternate: Skowron et al. (RCP 4.5)	
	RF	ERF	RF	ERF
O$_3$ short	25.1 ± 4.3	34.4 ± 9.9	20.1	27.6
CH$_4$	– 7.9 ± 2.9	– 18.7 ± 6.9	– 12.8	– 15.1
O$_3$ long	– 15.8 ± 5.9	– 9.3 ± 3.4	– 6.4	– 7.6
SWV	– 2.4 ± 0.9	– 2.8 ± 1.0	– 1.9	– 2.3
Net NO$_x$	1.0 ± 6.6	5.5 ± 8.1	– 1.1 ± 2.4	2.6 ± 6.0

This uncertainty has little impact on the results of the scenarios modelled in this work, mostly because we are not modelling the deployment of specific NO$_x$ mitigation measures via technology or different fuels. However, it would make our model extremely uncertain to assess and rank these measures, as highlighted as well in ref. 8.

Scenario classification

In order to compare the previously studied mitigation scenarios, it is relevant to analyse the relative evolution of temperature change due to CO$_2$ emissions and non-CO$_2$ effects. It can allow to classify the scenarios depending on the mitigation strategies used. In addition to the three previous scenarios, two additional ones are also used: an illustrative one (description below) and another that combines the "Low-carbon fuel" and "Operations" scenarios.

Figure 7 shows the evolution of temperature change due to non-CO$_2$ effects as a function of the temperature change due to CO$_2$ effects for each scenario. Each point on the curves represents a given year, with examples provided for the "Trend" scenario. Violet sloping lines represent several levels of total temperature change, so that the scenarios can be compared directly in terms of their total contribution. Black dotted lines correspond to different temperature multipliers for obtaining total temperature change from temperature change due to CO$_2$ emissions. For instance, a temperature multiplier of $\mu = 2$ means that CO$_2$ emissions and non-CO$_2$ effects induce a similar impact on the aviation temperature change. Note that the 2019 temperature multiplier is around 2.5, which is less than the ERF multiplier

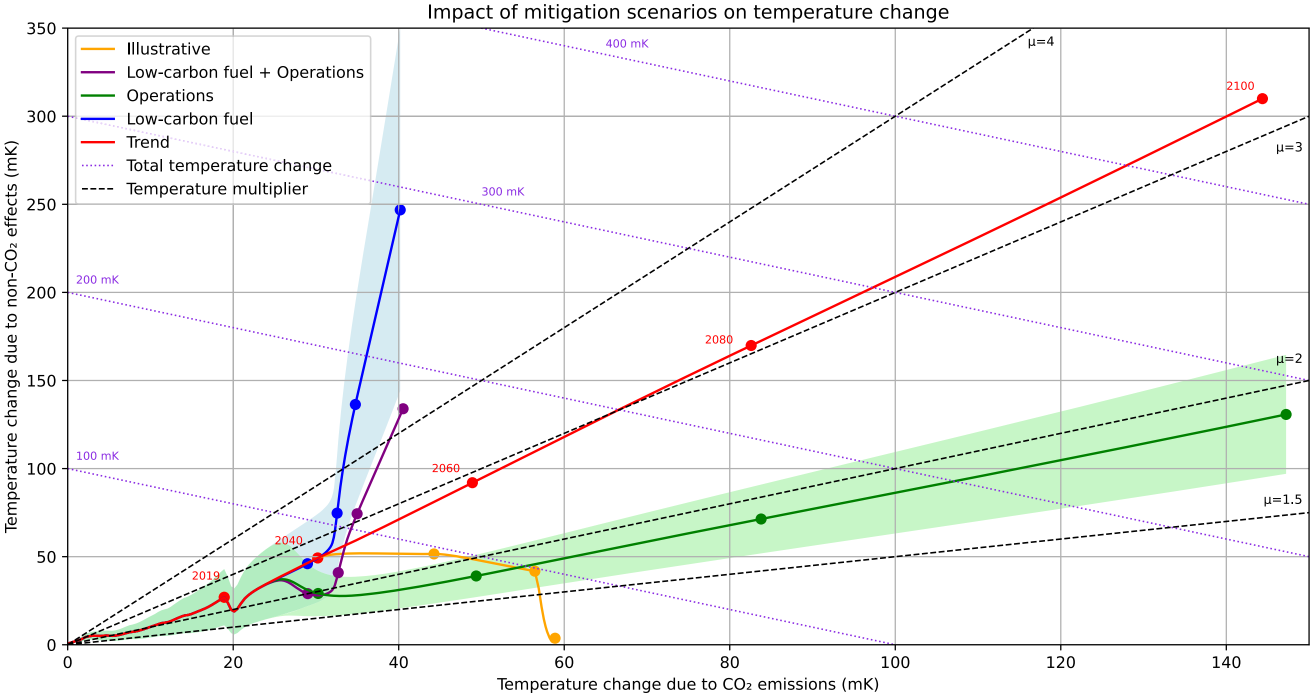


Fig. 7 | Comparison of the surface temperature change of mitigation scenarios. The graph allows their direct comparison, showing the contribution of CO_2 emissions and non-CO_2 effects to temperature change on the x- and y-axis. Total temperature change and temperature multiplier are also provided. A dot on each line corresponds to a year, some of which are shown for illustrative purposes.

(also called radiative forcing index) close to 3[1]. It is notable that Klöwer et al.[39] produced a similar figure considering equivalent emissions.

To understand this figure, one can analyse the evolution of the "Illustrative" scenario, in which emissions are reduced by 0.2% per year from 2040, then reduced by 1.5% per year from 2060, and finally halted in 2080. In this case, the temperature change due to non-CO_2 effects is stabilised between 2040 and 2060, but the total temperature still increases due to ongoing CO_2 emissions. Then, from 2060 to 2080, the total temperature change is stabilised, with the temperature decrease from non-CO_2 effects balancing the increase from CO_2 emissions. Finally, an important decrease in total temperature change is visible from 2080 with the halt of aviation emissions. It is interesting to note the evolution of the temperature multiplier over time, with non-CO_2 effects becoming less significant.

Regarding the mitigation scenario studied in this paper, one can see that low-carbon fuels allow a clear limitation to temperature increase from CO_2 emissions, but also an impact on non-CO_2 contribution. The mitigation scenario based on contrail avoidance has a stronger impact on non-CO_2 temperature increase, with even a decrease between 2030 and 2040, but no effects on the CO_2 contribution. Integrating uncertainties from Lee et al.[1] on contrails also shows that the low-carbon fuel mitigation scenario is subject to greater uncertainty. The last mitigation scenario ("Low-carbon fuel + Operations"), combining the two levers of action studied in this paper, is also presented, leading to a lower temperature increase by 2100. It is interesting to note that the temperature multipliers vary significantly. For instance, the "Operations" scenario leads to a temperature multiplier close to 2, while the combined one leads to a value of 4, increasing the relative contribution of non-CO_2 effects.

CO_2-equivalence metrics comparison

The concept of temperature multiplier used below differs from radiative forcing index, but also from conventional CO_2-equivalence metrics such as GWP or GTP. Although suitable for comparing effects of different natures over a time horizon, the latter are limited in their ability to reproduce impacts on temperature for SLCFs[40] as mentioned in the introduction. In the following, several conventional CO_2-equivalence metrics are estimated for aviation and compared to warming equivalent metrics obtained from the two climate models proposed in this paper.

These warming equivalent metrics are defined in such a way as to correspond to changes in temperature. In other words, if one were to integrate an inventory of equivalent CO_2 emissions using these warming equivalent metrics into a climate model, one would find a similar surface temperature change profile to that obtained by directly integrating the climate forcers into a climate model. For instance, the warming equivalent emissions can be obtained directly from those calculated in the GWP* approach, or by using annual temperature changes from climate models (e.g. in the FaIR approach).

For performing the comparison, the annual multiplier coefficient α, defined in Eq. (1), is introduced for the conventional CO_2-equivalence metrics. This equation can also be used directly in the case of the warming equivalent metrics obtained with GWP*. For FaIR, the ratio between total annual temperature change and annual temperature change from CO_2 emissions can be used for estimating α.

$$\alpha = \frac{E_{CO_2} + \sum_i E_{eq,i}}{E_{CO_2}} = 1 + \sum_i M_i \frac{E_i}{E_{CO_2}} \tag{1}$$

with E_{CO_2} the annual CO_2 emissions, $E_{eq,i}$ the annual equivalent emissions for the species i, E_i the annual emissions for the species i, and M_i the equivalent metric for the species i.

Figure 8 shows the historical evolution of the annual multiplier coefficient. Warming equivalent metrics are also provided using the GWP* and FaIR approaches, using a 10-year sliding average to simplify the analysis by avoiding highlighting annual changes that are not representative of the overall trend. The results are very different for conventional metrics and warming equivalent ones. It demonstrates once again that conventional metrics are not suitable for reproducing changes in temperature. The figure also shows that the annual multiplier coefficient is increasing for conventional metrics, due to the change in relative distribution of species emissions. Even if these conventional metrics are constant for each specie, the annual multiplier coefficient is changing. It is interesting to note that the evolution

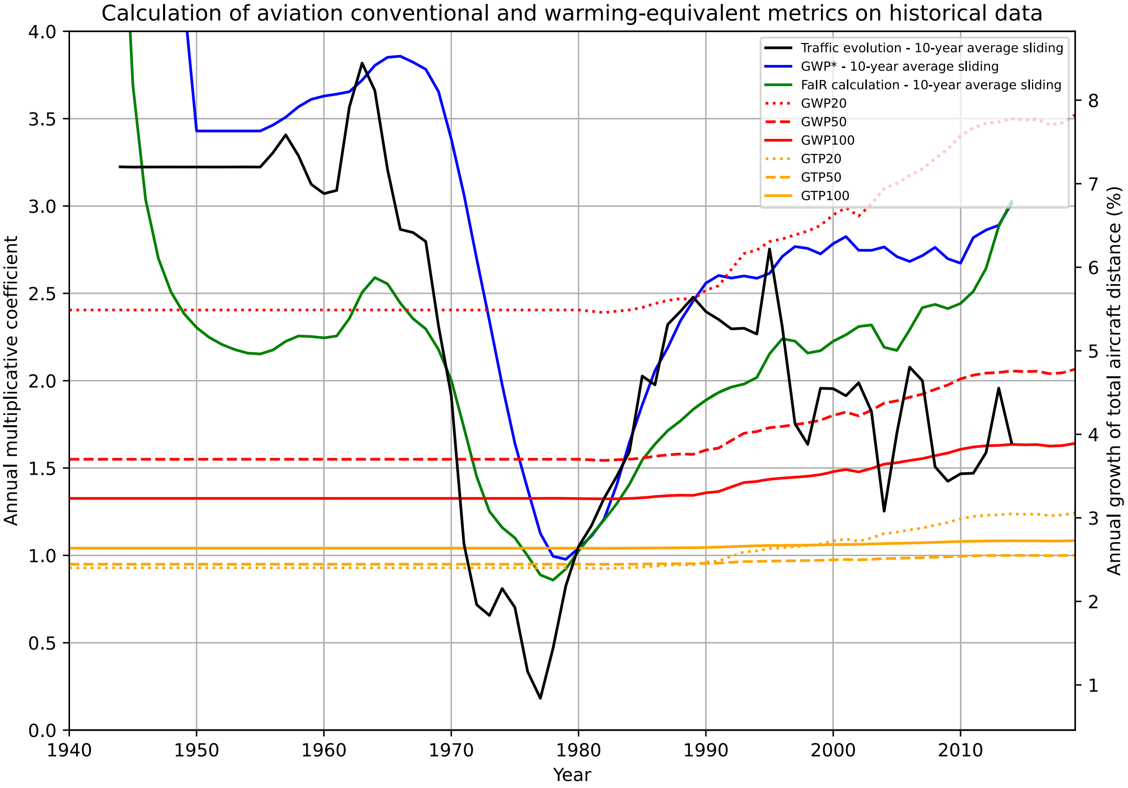


Fig. 8 | Comparison of conventional CO_2-equivalence metrics for historical aviation climate impacts. Warming equivalent metrics are also provided based on the climate models proposed in this paper.

of the warming equivalent metrics (and so of the temperature) is correlated with changes in air traffic.

Although conventional metrics are not adapted to temperature estimates, as shown by the historical analysis (see Fig. 8), it may be appropriate to evaluate them in prospective scenarios to determine which are closer to warming equivalent metrics. Figure 9 provides the results for the "Trend" scenario for different evolutions of air traffic. In the short term, none of the metrics is capable of reproducing changes in temperature. However, after 2040, one can see a convergence between certain metrics. In the case of an annual 3% growth in air traffic, GWP20 (which corresponds to high values) seems suitable. In the case of an air traffic stabilisation, low value metrics such as GTP are more suitable. However, none of the metrics are appropriate in the event of a reduction in air traffic, as the induced temperature change could be reduced. We obtain similar results whatever the mitigation scenario considered, the only difference being the final level of the multiplier reached. In a nutshell, except in the case of a reduction in air traffic where none of the metrics is suitable, the higher the level of air traffic, the more relevant it is to use conventional CO_2-equivalence metrics with high values in order to approximate temperature trends.

Discussions

Based on the models validation and results provided previously, several discussions are proposed in the following, concerning in particular the relevance of aviation lightweight climate models and the suitable CO_2-equivalence metrics

The two methods proposed here for calculating aviation's contribution to surface temperature change offer a simple approximation for simulating possible future scenarios and comparing different mitigation strategies. Calculations made with FaIR give a more realistic time response of temperature to CO_2 and SLCFs emissions, and offer the possibility of taking background emissions into account. Despite its lower level of complexity, GWP* shows very similar results in "usual" scenarios (without abrupt emissions changes), while enabling a straightforward approach, faster calculations and metrics estimates. GWP*, initially proposed in ref. 36 as an alternative warming equivalent metric better suited to reflect methane impacts compared to CO_2, has been since described by Meinshausen et al.[50] as a model rather than a metric, representative of "*a new class of 'micro climate models' (MCMs) that should be welcomed in the hierarchy of climate models*". Our original calibration of GWP* parameters to specific aviation non-CO_2 short term forcers, and its application, demonstrate that it can be used as a simplified model suitable for simulating the evolution of aviation non-CO_2 effects and dedicated mitigation scenarios. GWP* appears in general sufficient to enable for example ranking the most efficient mitigation strategies, while being conscious of the uncertainties, and aware that the climate effect in terms of temperature will be slower to appear in reality.

Our results highlight as well the important remaining scientific uncertainties on the quantification of the climate forcing of aviation non-CO_2 species, and thus when assessing the pertinence of mitigation measures, a point discussed extensively in Lee et al.[8]. In our model, the choice of parametrisation for the unit ERF significantly impacts the temperature benefit of contrails avoidance scenarios. For NO_x, especially with the uncertainties from ref. 14, there is a non-negligible chance that net NO_x effect of aviation will become net cooling in the future, even without any mitigation, due to the evolution of background concentrations as mentioned in the introduction. This is all the more problematic for evaluating NO_x reduction technologies, since the proposed ones generally have an adverse impact on weight or engine efficiency, and thus cause more CO_2 emissions as a trade-off, as discussed in ref. 8. Lastly, the forcing from aerosol-cloud interactions caused by aviation aerosols is highly uncertain as mentioned in the introduction, and has no best estimate given in ref. 1, while very recent works such as ref. 51 are giving a significant cooling estimate. This still missing quantification makes it problematic to assess the pertinence of acting on aviation fuel properties (sulphur and aromatic contents), for instance, while potentially ignoring a potentially comparable cooling effect. Indeed, in this paper, only their impacts on CO_2 emissions, contrails forcing and sulphur and black carbon radiative effects have been taken into account.

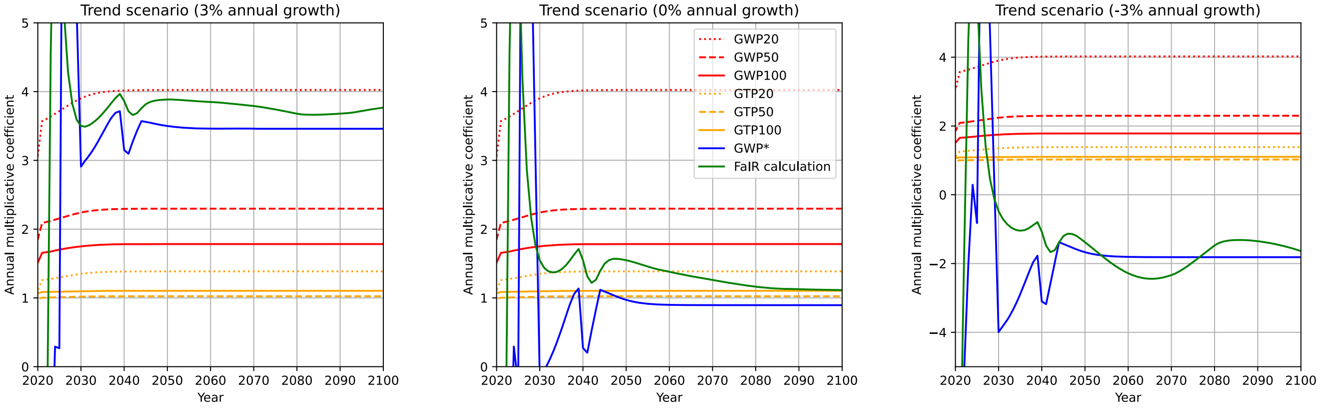


Fig. 9 | Comparison of CO_2-equivalence metrics for prospective aviation impacts. The results are provided for the "Trend" scenario with three different annual air traffic growth (+3%, 0%, −3%).

The lightweight models, such as the ones proposed here but also all the climate emulators mentioned in the introduction, which are quick and easy to parameterise, are fit for purpose and useful to illustrate and discuss the consequences of these uncertainties on aviation mitigation levers. This does not require necessarily the use of more complex models such as for example the non-linear climate-chemistry response model AirClim[23]. This state-of-the-art dedicated model is not open access and open source at the time of this writing, and the level of confidence in its results is difficult to assess for the reader, whereas these open-source simpler models offer a transparent display of their main parameters and associated uncertainties. Given these uncertainties, it is probably premature to draw definitive conclusions from *any* model concerning aviation non-CO_2 effects, while a quick, reactive and adjustable one is at least useful to assess the risk and opportunities of mitigation options. Nevertheless, the more complex 4D climate models are obviously required to continue work on non-CO_2 effects, in order to ultimately feed these lightweight models. In a nutshell, these types of lightweight models could complement more complex models, particularly for exploring mitigation scenarios for air transport.

Our work also contributes to the current very active debate on relevant CO_2-equivalence metrics for aviation in the context of policy making or mitigation choices for the industry, for example in refs. [8,52–55]. This discussion is important because the appropriate results could be used to include aviation non-CO_2 in emissions trading schemes, such as the European Union Emissions Trading System (EU-ETS), or emission pricing more broadly.

The shortcomings of conventional metrics, such as GWP or GTP taken on different time horizons, to properly account for aviation non-CO_2 and more generally SLCFs, are well documented. Nevertheless, we showed at least some trends that one can keep in mind concerning the choice of CO_2-equivalence metrics. Whatever the technological mitigation scenario, the more the air traffic is increasing, the more it is relevant to choose high value CO_2-equivalence metrics such as GWP20 to obtain an annual multiplier coefficient close to the ones corresponding to temperature trends. These metrics remain limited and not suitable for representing the temperature change, but have the advantages of being conventional.

The GWP* approach can be used to compute CO_2 warming equivalent emissions over a given period of time. It corresponds in fact to the amount of CO_2 that would have the same temperature impact as the considered SLCFs effect. GWP* and the related warming equivalent emissions could then be used as a "dynamic" metric (in that it will vary year on year for reproducing a temperature change profile). However, the use of GWP* as a CO_2-equivalence metric raises methodological and ethical issues. The latter are particularly studied for the case of methane and are well described in ref. [50]: one could for instance mention that this metric penalises new emitters[56]. In any case, the metric choice implies an arbitration of the burden sharing between present and future generations, a topic not addressed in this paper. Additionally, a recent study from Megill et al.[54] also showed the limitations of GWP* as a metric, rejecting it mainly because it is not temporally stable and not easy to implement. Nevertheless, the authors highlight its neutrality and consistency when computing temperature for future fleet scenarios, especially when weighted by efficacy as we are doing here. Instead, they advocate the use of ATR and EGWP (efficacy-weighted GWP), but it should be noted that both also require the use of a climate model for their estimation.

At a minimum, it is widely agreed, as reported in refs. [8,52], that quantifying SLCFs agents, including aviation non-CO_2, separately in emission reporting is a much better choice than aggregating those in usual CO_2-equivalence metrics. GWP*, FaIR or any model can then be used to compute a relevant aggregated temperature impact, and most importantly to recompute it iteratively as the scientific understanding and quantification of aviation non-CO_2 forcers progresses. In this line of thought, the IPCC is currently (as of 2024) scoping and developing a "Methodology Report on Short-lived Climate Forcers"(https://www.ipcc.ch/event/scoping-meeting-for-a-methodology-report-on-short-lived-climate-forcers-slcfs) for an intended publication in 2027, a work that should progress the topic of SLCFs accounting, and which is understood to move away from the legacy UNFCCC (United Nations Framework Convention on Climate Change) reporting in terms of GWP_{100} for all. This publication will certainly help in setting CO_2-equivalence metrics and objectives for the aviation sector in relation to emissions from all human activities, including SLCFs.

More broadly, like the authors in ref. [8], we believe that the debate on the alleged arbitrariness in the choice of metrics, and the associated difficulty in relevantly assessing mitigation measures, is rather overstated, because lightweight climate models can offer an easy-to-use and fairly unambiguous means of assessing mitigation measures, setting aside of course the uncertainties on the quantification of individual impacts.

In other words, reasoning in terms of temperature impact remains probably the best choice for obtaining results on mitigation levers. Indeed, average temperature change is one of the ultimate indicators used to set overall climate policy goals, such as the Paris Agreement's "well below 2 °C above pre-industrial levels"[57]. This value is also simpler to use than region-specific temperature change. Then, temperature change expressed as a time series allows for the crucial arbitration between short-term and long-term climate impacts. For example, in a 1.5 °C scenario, limiting the peak and duration of warming can help avoid long-term or irreversible damage to ecosystems or society[58]. Starting from such an overall climate objective linked to a clear policy goal, a specific objective in terms of temperature impact over time could then be cascaded down to aviation, inscribed within a global non-aviation emissions scenario. An example of this is a maximum induced temperature change target associated with no additional warming after a given date, as discussed in refs. [22,35]. Doing this accurately as a function of time is particularly important because of the relative weight of non-CO_2 effects in aviation climate impact, and especially for operational contrail mitigation which,

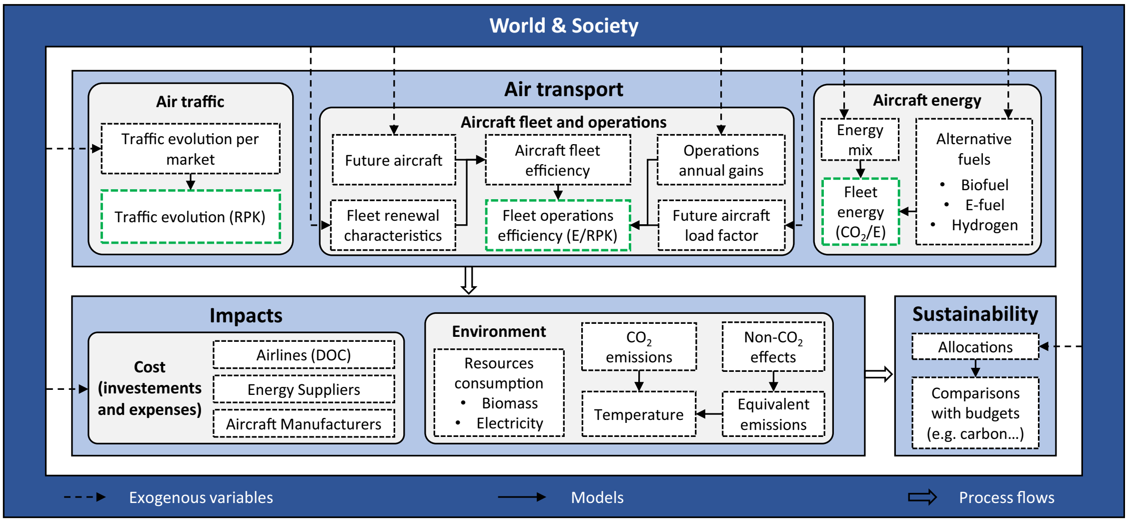


Fig. 10 | Simplified architecture of AeroMAPS. This work contributes to improve the current climate model and to add a new one to the Environment module.

if proven effective, could provide a significant temperature benefit over the next few decades.

This discussion highlights the fact that simple models that directly assess temperature change over time, such as those presented here, could help to identify the more efficient and timely levers in this context. Nevertheless, the use of conventional metrics will remain key for many other applications, such as aircraft design, trajectory optimisation, and policy (e.g. multipliers for emission pricing)[54]. The use of lightweight models and conventional metrics could even be coupled to take advantage of their respective benefits. For example, once the most effective levers have been identified using lightweight models, appropriate conventional CO_2-equivalence metrics could then be used to incentivise the deployment of the corresponding levers. Such methods and metrics could be for instance used in dedicated emissions trading schemes, independent of those focused on CO_2 emissions which can rely on carbon budgets.

While this study provides consistent models for assessing various aviation mitigation strategies on climate change, several limitations must be acknowledged. These limitations also highlight areas for future research to further refine and enhance the models and methodologies used.

First, the lightweight models used in this study are designed for simplicity and computational efficiency. However, they involve assumptions that do not capture all the complexities of real-world climate dynamics. Specifically, the models do not adequately account for the regional dependency of the radiative impact of some species, including local saturation effects, particularly in contrail formation and associated climate impact. Similarly, the effect of background past and future emissions for NO_x is not systematically included. Future improvements should aim to incorporate regionalised and parametrised models to enhance the accuracy of the results.

In particular, in our approach with FaIR, we chose to rely on its default settings and parametrisation. Further refinement of its parameter settings is likely needed to enhance its accuracy for our specific application. Future research should focus on fine-tuning FaIR parameterisation, calibrating against results from more complex models, ensuring it captures the nuances of aviation-related climate impacts effectively. In addition, a similar work could be performed using other climate emulators, which may or may not be better at assessing specific effects for aviation, such as cloudiness or the methane cycle.

Then, the model validation is based on a limited number of references, for which the settings were not necessarily known. A detailed comparison between lightweight models and advanced 4D models, if possible open-source, is needed to better understand their relative strengths and limitations. Such comparisons will help to validate the simpler models and identify areas where they may need refinement.

It must be acknowledged that our models (but also more complex models) are probably not yet at the level required to robustly inform policy making, given the above limitations and the uncertainties, both on aviation climate impacts and mitigation levers effects, which have been widely discussed in this paper and apply to any model. Still, by explicitly propagating uncertainties, it might already be useful to at least identify specific strategies which are robust enough, both to uncertainties and possibly to background emission scenarios. The continuous integration of latest results in the field, from results from more complex models and observational studies, is required to increase confidence.

More broadly, there is a need to develop a comprehensive family of climate models that can cater to different levels of complexity and detail. This family should range from simple, fast-running models for preliminary assessments to detailed, high-resolution 4D models for in-depth analysis. Developing such a suite of models would allow researchers and policymakers to choose the appropriate tool for their specific needs, balancing accuracy, complexity, and computational requirements.

Lastly, concerning the CO_2-equivalence metric discussion, only a small number of metrics have been considered here. It would be interesting to automate the calculation of a multitude of metrics in AeroMAPS to compare their performance. Overall, future research should explore how these models can inform and be informed by economic policies and regulatory measures, ensuring practical and effective implementation of mitigation strategies.

Methods

This section includes a description of the methods used in this paper. In a first step, the AeroMAPS framework, used in this paper for simulating aviation historical data and prospective scenarios, is described. In a second step, some new models for taking into account non-CO_2 mitigation in AeroMAPS are presented. In the last step, the climate models developed for this paper and AeroMAPS are detailed, with in particular the description and settings of the two approaches based on GWP* and FaIR.

AeroMAPS

AeroMAPS is an open-source framework for performing multidisciplinary assessments of prospective scenarios for air transport[42]. A simplified architecture of the current version of AeroMAPS is shown in Fig. 10.

The framework relies on a set of exogenous inputs such as air traffic growth, improvements in aircraft technology and potential gains in operational efficiency. The input values are fed into the main *air transport* module, which simulates the temporal evolution of the air transport system, including the air traffic, aircraft fleet and energy required to operate the latter. The evolution of air traffic is modelled by simple exponential growths, the value of which can be specified per period and per category (short/medium/long-haul passengers and freight). This demand is then satisfied by an aircraft fleet whose composition and performance can be defined by using fleet renewal models, and introducing new aircraft into the fleet as discrete-time events. Detailed performance data for each aircraft type are required, for instance derived from comprehensive aircraft design tools, along with its anticipated year of service commencement, final market share, and rate of fleet penetration. The type of energy carrier used by each aircraft type has to be specified, differentiating between drop-in fuels (such as kerosene, electrofuel, and biofuel) and non-drop-in fuels (like hydrogen), with explicit proportions of each outlined by the user. Finally, several models allow a description of the energy carriers used by the fleet over time. For instance, explicit proportions of each pathway and their corresponding characteristics (e.g. emission factor or efficiency) have to be specified for different crossing points. In particular, an electricity mix (e.g. high/low-carbon grid or dedicated renewable) can be chosen for the production of electricity-based fuels.

In a second step, two other modules are used to estimate the *impacts* of the user-defined scenario from an environmental and economic point of view, and to assess its *sustainability*. The economic assessment involves the use of cost models to estimate, among other things, the Direct Operating Costs (DOC), taking into account energy costs, maintenance costs and carbon taxes. The environmental assessment includes climate models to estimate effective radiative forcing (ERF) and temperature change, both for CO_2 and non-CO_2 effects. Initially developed in ref. 38, estimating equivalent emissions with the GWP* method (see section dedicated to climate models) calibrated from ref. 1, new climate models are proposed in this paper. The environmental module also estimates the consumption of biomass and electricity resources. Finally, a comparison of these impacts with sustainability targets (e.g. a carbon budget allocated to aviation) completes the scenario assessment.

Non-CO_2 mitigation modelling

In addition to the mitigation levers of action available in AeroMAPS for reducing CO_2 emissions, two levers are implemented for reducing non-CO_2 effects, and particularly contrails: the use of alternative fuels and operational strategies for avoiding contrails.

Beyond the reduction of CO_2 emissions, the use of alternative fuels modifies the climate impact associated to non-CO_2 emissions. Notably, the use of drop-in fuels influences emissions of sulphur dioxide and soot. Concerning hydrogen, its use as a fuel can alter the formation and characteristics of contrails. Note that hydrogen is not considered in this paper due to important uncertainties concerning its climate impact, especially contrails as highlighted in ref. 59. However, the implementation of sensitivities to its emissions (including spurious H_2 emissions) and contrails would be straightforward in our model, once the scientific consensus has progressed.

The emissions of SO_2, the precursor of sulphate aerosols, mainly depend on the sulphur content of the fuel, which in turn is influenced by the origin of crude oil and the refinery process. That is why alternative drop-in fuels (e.g. biofuels and electrofuels) do not emit SO_2, as their sulphur concentration is zero.

The use of alternative fuels also leads to reduction in airborne soot emissions, offering a potential strategy to mitigate the climate impact of contrails. This results from the lower aromatic contents in the synthetic fuels as measured in Voigt et al.[6]. Low aromatic content can also be achieved with active hydrotreatment of fossil kerosene, an alternative fuel type called hydrotreated fuel here. Sulphur can also be quasi-eliminated from fossil kerosene through hydrotreatment. The radiative impact of a given contrail cirrus coverage depends on the number and size of ice crystals. The reduction in soot emissions, leading to changes in microphysical properties, can be expected to modify its climate impact analogously to the effects observed in liquid clouds when there is a decrease in aerosol loading in the atmosphere. Burkhardt et al.[20] estimate the net global radiative forcing as a fraction of the initial concentration of ice crystals in the engine plume. Based on this estimation, Eq. (2) is used to estimate the contrails sensitivity from a fuel $SE_{\text{contrails, fuel}}$ as a function of the reference value for fossil kerosene $SE_{\text{contrails, kerosene}}$. PN represents the normalised number of initial ice particles. This normalised number depends on the type of fuel, considered here as 1 for kerosene, 0.4 for biofuel and electrofuel (mean value based on ref. 6), and 0.7 for hydrotreated fuel.

$$SE_{\text{contrails, fuel}} = SE_{\text{contrails, kerosene}} \cdot \sqrt{PN} \tag{2}$$

Note that the non-CO_2 climate benefits from alternative fuels are not fully established yet. This simple modelling of the impact of alternative fuels, sourced from a single study, will likely need to be updated in the future. Improved models could be based on new results, for instance from ref. 7, and further test campaigns and studies on this very active field of research.

The modelling of contrail avoidance strategies relies on the use of logistic functions. These models are particularly relevant for modelling the introduction of a product into a market[60]. As a consequence, they are used in several disciplinary fields, such as economics, sociology, demographics, technology and medicine[61–63]. They are also used for aircraft fleet renewal, for instance in AeroMAPS and in ref. 26. Here, Eq. (3) is used for estimating the reduction in contrails ERF $R(t)$ for the year t. A similar model is used to integrate a potential overconsumption of fuel due to the implementation of these strategies.

$$R(t) = \frac{R_f}{1 + e^{-k(t-t_0)}} \tag{3}$$

where R_f is the final ERF reduction enabled by contrails avoidance, and k and t_0 coefficients to set the timing and the speed of change.

Aviation climate modelling

The climate models developed for AeroMAPS aim at estimating the temperature increase due to aviation CO_2 and non-CO_2 effects. To do this, aviation emissions are estimated at the fleet level using time series data on fuel consumption and emission indices. Then, the induced effective radiative forcings (ERFs) are calculated using sensitivities to emissions expressed as ERF per unit emission, or per distance flown for contrails. Finally, the temperature increase estimate relies on two different methods as shown in Fig. 11. In the following, details are provided on the sensitivities to emissions and on the two climate modelling methods used.

The sensitivities to emissions from Lee et al.[1] are used by default to compute the ERF of each species. Lee et al. calculated best estimates of individual aviation sensitivity terms, along with the associated uncertainties, based on normalised values of ERF per unit emission, or flown distance for contrails. The sensitivity of the impact of aerosols interaction with clouds is left at zero as it remains undetermined. These default sensitivities to emissions and some uncertainty ranges are summarised in Table 2.

In addition, alternative quantifications of sensitivities to emissions from newer publications are considered. For contrails, the overall forcing computed by Teoh et al.[46] for the year 2019, converted as a sensitivity to distance from the total 2019 flown distance, is proposed. For NO_x-related climate impacts, sensitivities per species from Skowron et al.[14], using an updated CH_4 parametrisation, are implemented as well.

Note that sensitivities expressed in RF are converted to ERF sensitivities using the ERF/RF ratios from Lee et al. It shall be emphasised that the reference ERF/RF figures in ref. 1 are sourced from very few dedicated studies on the topic, and for O_3 and CH_4 even from runs from a single model originally in ref. 64, and thus are provided without associated uncertainties. This is another likely important and non quantified source of uncertainty in our model and similar work such as ref. 39.

It is also worth mentioning that we are using ERF rather than RF to compute GWP* since it is significantly more relevant for the impact on temperature of aviation non-CO_2 species, as the ERF/RF ratios significantly differs from 1. Some authors such as Megill et al.[54] use the term EGWP*

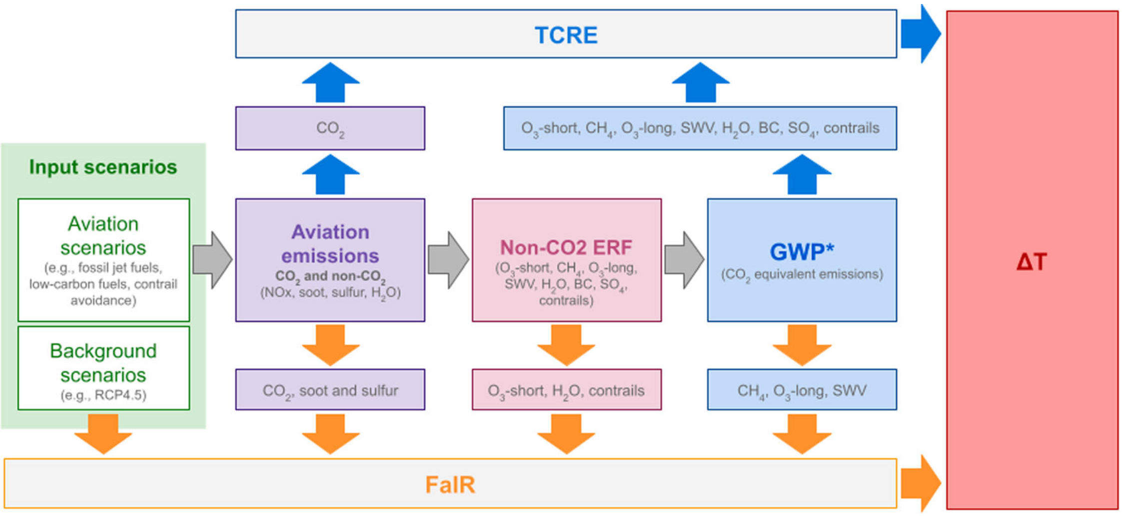


Fig. 11 | Principle schematics of the two climate modelling options, with the GWP* approach in blue and the FaIR approach in orange. The different boxes correspond to intermediate calculations.

Table 2 | Table of sensitivities to emissions in ERF used in the model

Emission species	ERF sensitivities to emissions	
Contrails	57.4 (17, 98)/2018 km	mW m^{-2}/km
NO_x: O_3 short	34.4 ± 9.9	
NO_x: CH_4	− 18.7 ± 6.9	
NO_x: O_3 long	− 9.3 ± 3.4	mW m^{-2}/TgN
NO_x: SWV	− 2.8 ± 1.0	
Net NO_x	5.5 ± 8.1	
Black carbon (radiative)	100.7	mW m^{-2}/TgBC
SO_x (radiative)	−19.9	mW m^{-2}/TgSO_2
H_2O	0.0052	mW m^{-2}/TgH_2O
Aerosol/cloud	0	mW m^{-2}

(efficacy-weighted GWP*) for a GWP* computed from ERF rather than RF, which corresponds to what we call GWP* in this paper.

On the one hand, the first approach used in this paper for calculating temperature change relies on the concepts of transient climate response to cumulative emissions of carbon dioxide (TCRE) and CO_2 equivalent emissions. The TCRE coefficient directly links the cumulative CO_2 emissions to the temperature increase. Each 1000 GtCO_2 of cumulative CO_2 emissions is estimated to cause an increase in the global surface temperature of 0.27 °C to 0.63 °C, with a best estimate of 0.45 °C[65]. Nevertheless, this approach is not suitable for non-CO_2 effects. A simple solution is to define equivalent emissions in order to estimate the total contribution of aviation to climate change ΔT_t using Eq. (4). It is assumed that the individual effects of aviation climate effects are independent of each other when estimating the temperature change due to aviation[39].

$$\Delta T_t = TCRE\left(\sum_t E_{CO_2} + \sum_{t,i} E_{CO_2\text{-we},i}\right) \tag{4}$$

with E_{CO_2} the annual CO_2 emissions and $E_{CO_2\text{-we},i}$ the annual warming equivalent CO_2 emissions for the different aviation non-CO_2 effects.

Different methods are available for estimating equivalent emissions. The common approach is the use of Global Warming Potentials (GWPs). However, in this case, converting SLCFs into CO_2 equivalent emissions presents a misleading picture of their impact on global temperature, which is the case for aviation non-CO_2 effects. Allen et al.[36] propose an alternative approach to quantify the contribution of non-CO_2 emissions to future temperature changes, known as GWP*. This method captures the fundamentally different behaviour of short- and long-lived climate pollutants[40]. Equations (5) and (6) are used in this paper based on recent developments[66,67].

$$E_{CO_2\text{-we},i} = \frac{g(s_i)}{AGWP_H}\left((1-s_i)\,H\,\frac{\Delta ERF_i}{\Delta t_i} + s_i\,ERF_i\right) \tag{5}$$

$$\text{where } g(s_i) = \frac{1-e^{-s_i/(1-s_i)}}{s_i} \tag{6}$$

with $AGWP_H$ the Absolute Global Warming Potential of CO_2 over a time horizon H of 100 years[68,69], ERF_i the Effective Radiative Forcing of the different non-CO_2 effects, and s_i and Δt_i coefficients for the GWP* method quantifying in particular the impact of short-term effects.

In this paper, a time horizon of H = 100 years is used according to established practice[36]. In fact, the results of GWP* are insensitive to this choice as long as H is much longer than the lifetime of the SLCF, a condition met by all short-term forcers from aviation included in our model. The choice of Δt = 20 years is made by Allen et al.[36] and appears to work well for methane[67]. Concerning aviation non-CO_2 effects, Lee et al.[1] assume that Δt = 20 years is a consistent value. However, for climate pollutants with shorter lifespans, a lifetime of less than 20 years may be more suitable[70]. Similarly, a calibration for methane of $s = 0.25$ is justified in ref. 66. However, for aviation non-CO_2 effects, a value of $s = 0$ is chosen by Lee et al.

Within this study, we consider three different settings for calibrating GWP* for aviation non-CO_2 effects, which are detailed in the following. The performance of these different settings, analysed in the “Results” section, is also briefly recalled.

Firstly, the settings from Lee et al.[1] are considered with Δt=20 years and $s = 0$ for all the aviation non-CO_2 effects. These settings correspond to the ones initially used in the AeroMAPS framework. They are however limited for representing abrupt or short-term changes in aviation SLCF emissions. These settings are indicated as *Lee et al. settings* in the paper.

Secondly, these settings are updated by separating non-CO_2 effects linked to methane decrease due to NO_x emissions from the others. For the species linked to methane decrease, updated settings from ref. 66 are used, with Δt=20 years and $s = 0.25$. For the other effects, Δt = 1 year and $s = 0$ are chosen for taking into account the very short lifetime of these species. With

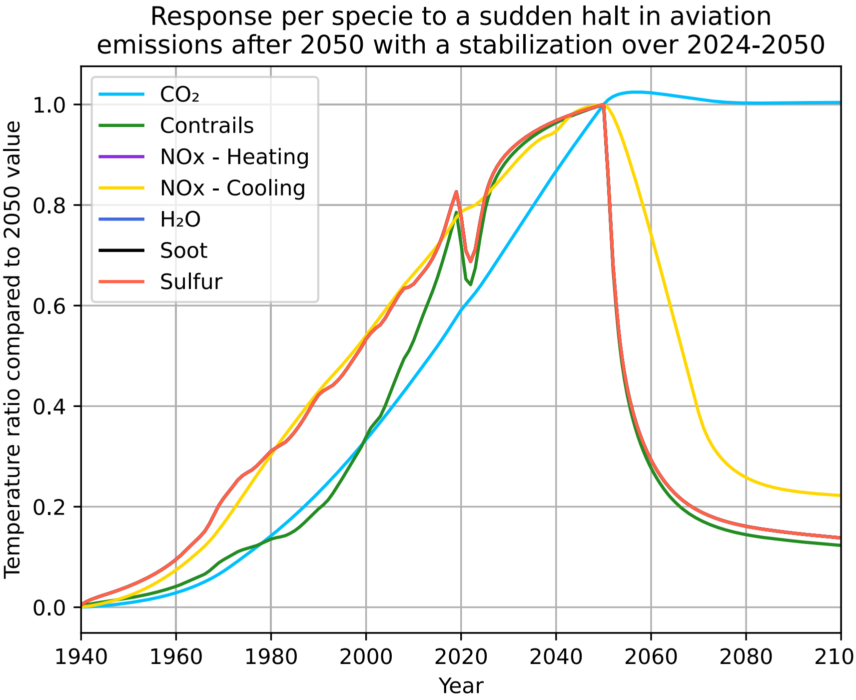


Fig. 12 | Response per species to a sudden halt in aviation emissions with FaIR method for calibrating GWP*, relative to 2050 values. The sudden halt in emissions appears in 2050, including COVID-19 over 2020–2024 and constant emissions over 2024–2050. The effect of contrails fades much faster than that of methane associated with NO_x emissions or that of CO_2 emissions.

these settings, abrupt or short-term changes in aviation SLCF emissions are better represented, but there is no inertia in the temperature response. These settings are indicated as *updated settings* in the paper.

Lastly, the previous settings are calibrated for the Δt of the non-CO_2 effects not related to methane decrease due to NO_x emissions, by using the FaIR approach (described in the next section) as a reference. Figure 12 shows the temperature response to a sudden halt in aviation emissions in 2050 (similar scenario than the one studied in “Results” section) for the different species. The response of species linked to methane decrease due to NO_x emissions is taken as a reference because of its accurate calibration for GWP*. One can see that after a period of $\Delta t = 20$ years, around 40% of the temperature change is still present. Assuming a similar method for the other non-CO_2 effects, a value of $\Delta t = 6$ years is required for reaching the same reduction in temperature. The results obtained from these settings are consistent in a first approach with the radiative forcing and temperature responses observed in other investigations[5,19,39]. These settings are indicated as *selected settings* in the paper.

On the other hand, the second approach used in this paper for calculating temperature change relies on the use of a climate emulator which is a simplified climate model. In this work, the Finite Amplitude Impulse Response model (FaIR) model is used[31]. FaIR comprises a system of six equations that prove adequate in encapsulating the overall global response of the climate system to greenhouse gas and aerosol emissions. The model computes the surface temperature response to variations in global radiative forcing and/or emissions. To ensure the model’s temperature response is maximally accurate and that the absolute value is realistic, it is essential to consider global emissions in addition to those from aviation.

Within this study, only world CO_2 and CH_4 emissions are used, based on four representative concentration pathways (RCP): RCP2.6, RCP4.5, RCP6.0 and RCP8.5[71]. RCP4.5 is used by default in this paper. The response of the carbon cycle to temperature rise is determined by FaIR parameters settings (based on default ones and chosen for obtaining a TCRE close to the median one used in this paper) and emissions from these scenarios. All the settings chosen are available in the source code of AeroMAPS. Initially, the model is used considering the combined contributions of all species, including aviation emissions and the RCP scenarios. To ascertain each species’ individual contribution, the model is executed while excluding each species’ impact sequentially. The difference between these two calculations provides the contribution to the warming of each species. The sum of these different contributions represents the overall temperature change induced by aviation.

The FaIR model allows for the inclusion of each species’ contribution in the form of emissions, concentrations or forcings. In this approach, H_2O and short-term O_3 increase (from NO_x emissions) are provided as forcings. Sulphur and soot are integrated as emissions, although their influence on climate warming is denoted within FaIR as direct and indirect aerosol forcings. Finally, while CH_4 can be supplied as a forcing, accommodating CH_4 emissions from RCP scenarios necessitates the inclusion of aviation’s contribution in the form of emissions. As a consequence, equivalent emissions using GWP* method are estimated for CH_4 depletion from NO_x emissions, and added to CO_2 impacts as emissions. The contributions from long-term O_3 and SWV decrease from NO_x emissions are treated separately but similarly, given their association with methane’s depletion[13].

Data availability

All data and results are available in the code GitHub repository.

Code availability

The source code of AeroMAPS is available on GitHub at https://github.com/AeroMAPS/AeroMAPS. It includes all the models (in particular the climate ones), a basic graphical user interface, a documentation and some examples via Jupyter Notebooks. The source code for reproducing the application of this paper is included in AeroMAPS in the Jupyter Notebook entitled “examples_climate_application.ipynb”.

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References

1. Lee, D. et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* **244**, 117834 (2021).
2. Delbecq, S., Fontane, J., Gourdain, N., Planès, T. & Simatos, F. Sustainable aviation in the context of the Paris Agreement: A review of prospective scenarios and their technological mitigation levers. *Prog. Aerosp. Sci.* **141**, 100920 (2023).
3. Teoh, R., Schumann, U., Majumdar, A. & Stettler, M. E. J. Mitigating the climate forcing of aircraft contrails by small-scale diversions and technology adoption. *Environ. Sci. Technol.* **54**, 2941–2950 (2020).

4. Grewe, V., Dameris, M., Fichter, C. & Lee, D. S. Impact of aircraft NOx emissions. Part 2: Effects of lowering the flight altitude. *Meteorologische Z.* **11**, 197–205 (2002).
5. Frömming, C. et al. Aviation-induced radiative forcing and surface temperature change in dependency of the emission altitude. *J. Geophys. Res. Atmos.* **117**, D19104 (2012).
6. Voigt, C. et al. Cleaner burning aviation fuels can reduce contrail cloudiness. *Commun. Earth Environ.* **2**, 114 (2021).
7. Märkl, R. S. et al. Powering aircraft with 100 % sustainable aviation fuel reduces ice crystals in contrails. *Atmos. Chem. Phys.* **24**, 3813–3837 (2024).
8. Lee, D. S. et al. Uncertainties in mitigating aviation non-CO2 emissions for climate and air quality using hydrocarbon fuels. *Environ. Sci. Atmos.* **3**, 1693–1740 (2023).
9. Digby, R. A., Gillett, N. P., Monahan, A. H. & Cole, J. N. An observational constraint on aviation-induced cirrus from the COVID-19-induced flight disruption. *Geophys. Res. Lett.* **48**, e2021GL095882 (2021).
10. Gettelman, A., Chen, C.-C. & Bardeen, C. G. The climate impact of COVID-19-induced contrail changes. *Atmos. Chem. Phys.* **21**, 9405–9416 (2021).
11. Quaas, J., Gryspeerdt, E., Vautard, R. & Boucher, O. Climate impact of aircraft-induced cirrus assessed from satellite observations before and during COVID-19. *Environ. Res. Lett.* **16**, 064051 (2021).
12. Schumann, U., Bugliaro, L., Dörnbrack, A., Baumann, R. & Voigt, C. Aviation contrail cirrus and radiative forcing over Europe during 6 months of COVID-19. *Geophys. Res. Lett.* **48**, e2021GL092771 (2021).
13. Grewe, V., Matthes, S. & Dahlmann, K. The contribution of aviation NOx emissions to climate change: are we ignoring methodological flaws? *Environ. Res. Lett.* **14**, 121003 (2019).
14. Skowron, A., Lee, D. S., De León, R. R., Lim, L. L. & Owen, B. Greater fuel efficiency is potentially preferable to reducing NOx emissions for aviation's climate impacts. *Nat. Commun.* **12**, 564 (2021).
15. Terrenoire, E. et al. Impact of present and future aircraft NOx and aerosol emissions on atmospheric composition and associated direct radiative forcing of climate. *Atmos. Chem. Phys.* **22**, 11987–12023 (2022).
16. Kärcher, B., Mahrt, F. & Marcolli, C. Process-oriented analysis of aircraft soot-cirrus interactions constrains the climate impact of aviation. *Commun. Earth Environ.* **2**, 113 (2021).
17. Zhu, J. et al. Decreased aviation leads to increased ice crystal number and a positive radiative effect in cirrus clouds. *AGU Adv.* **3**, e2021AV000546 (2022).
18. Varotsos, C., Krapivin, V., Mkrtchyan, F. & Zhou, X. On the effects of aviation on carbon-methane cycles and climate change during the period 2015-2100. *Atmos. Pollut. Res.* **12**, 184–194 (2021).
19. Dahlmann, K. et al. Climate-compatible air transport system – climate impact mitigation potential for actual and future aircraft. *Aerospace* **3**, 38 (2016).
20. Burkhardt, U., Bock, L. & Bier, A. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. *npj Clim. Atmos. Sci.* **1**, 37 (2018).
21. Lee, D. S. et al. Aviation and global climate change in the 21st century. *Atmos. Environ.* **43**, 3520–3537 (2009).
22. Sacchi, R. et al. How to make climate-neutral aviation fly. *Nat. Commun.* **14**, 3989 (2023).
23. Grewe, V. & Stenke, A. AirClim: an efficient tool for climate evaluation of aircraft technology. *Atmos. Chem. Phys.* **8**, 4621–4639 (2008).
24. Hein, R. et al. Results of an interactively coupled atmospheric chemistry–general circulation model: Comparison with observations. In *Annales Geophysicae*, vol. 19, 435–457 (Copernicus Publications Göttingen, Germany, 2001).
25. Mahashabde, A. et al. Assessing the environmental impacts of aircraft noise and emissions. *Prog. Aerosp. Sci.* **47**, 15–52 (2011).
26. Grewe, V. et al. Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects. *Nat. Commun.* **12**, 1–10 (2021).
27. Dray, L. et al. Cost and emissions pathways towards net-zero climate impacts in aviation. *Nat. Clim. Change* **12**, 956–962 (2022).
28. Meinshausen, M., Raper, S. C. & Wigley, T. M. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6–Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11**, 1417–1456 (2011).
29. Sandstad, M. et al. CICERO Simple Climate Model (CICERO-SCM v1. 1.1) – an improved simple climate model with a parameter calibration tool. *Geosci. Model Dev.* **17**, 6589–6625 (2024).
30. Gasser, T. et al. The compact Earth system model OSCAR v2.2: description and first results. *Geosci. Model Dev.* **10**, 271–319 (2017).
31. Leach, N. J. et al. FaIR v2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration. *Geoscientific Model Dev.* **14**, 3007–3036 (2021).
32. Terrenoire, E., Hauglustaine, D., Gasser, T. & Penanhoat, O. The contribution of carbon dioxide emissions from the aviation sector to future climate change. *Environ. Res. Lett.* **14**, 084019 (2019).
33. Ivanovich, C. C., Ocko, I. B., Piris-Cabezas, P. & Petsonk, A. Climate benefits of proposed carbon dioxide mitigation strategies for international shipping and aviation. *Atmos. Chem. Phys.* **19**, 14949–14965 (2019).
34. Boucher, O., Borella, A., Gasser, T. & Hauglustaine, D. On the contribution of global aviation to the CO_2 radiative forcing of climate. *Atmos. Environ.* **267**, 118762 (2021).
35. Brazzola, N., Patt, A. & Wohland, J. Definitions and implications of climate-neutral aviation. *Nat. Clim. Change* **12**, 761–767 (2022).
36. Allen, M. et al. A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Clim. Atmos. Sci.* **1**, 16 (2018).
37. Allen, M. et al. Ensuring that offsets and other internationally transferred mitigation outcomes contribute effectively to limiting global warming. *Environ. Res. Lett.* **16**, 074009 (2021).
38. Planès, T., Delbecq, S., Pommier-Budinger, V. & Bénard, E. Simulation and evaluation of sustainable climate trajectories for aviation. *J. Environ. Manag.* **295**, 113079 (2021).
39. Klöwer, M. et al. Quantifying aviation's contribution to global warming. *Environ. Res. Lett.* **16**, 104027 (2021).
40. Lynch, J., Cain, M., Pierrehumbert, R. & Allen, M. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short-and long-lived climate pollutants. *Environ. Res. Lett.* **15**, 044023 (2020).
41. Shukla, P. et al. Contribution of working group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, 2022).
42. Planès, T., Delbecq, S. & Salgas, A. AeroMAPS: a framework for performing multidisciplinary assessment of prospective scenarios for air transport. *J. Open Aviat. Sci.* **1** (2023).
43. International Civil Aviation Organization (ICAO). Report on the feasibility of a long-term aspirational goal. https://www.icao.int/environmental-protection/LTAG/Documents/REPORT%20ON%20THE%20FEASIBILITY%20OF%20A%20LONG-TERM%20ASPIRATIONAL%20GOAL_en.pdf (2022).
44. Air Transport Action Group (ATAG). Waypoint 2050. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf (2021).
45. Matthes, S. et al. Climate-optimized trajectories and robust mitigation potential: Flying ATM4E. *Aerospace* **7**, 156 (2020).
46. Teoh, R. et al. Global aviation contrail climate effects from 2019 to 2021. *Atmos. Chem. Phys.* **24**, 6071–6093 (2024).
47. Bickel, M., Ponater, M., Bock, L., Burkhardt, U. & Reineke, S. Estimating the effective radiative forcing of contrail cirrus. *J. Clim.* **33**, 1991–2005 (2020).

48. Bickel, M. et al. *Estimating the climate efficacy of contrail cirrus on surface temperature* (EGU24 – Copernicus Meetings, 2024).
49. Ponater, M., Bickel, M., Bock, L. & Burkhardt, U. Towards determining the contrail cirrus efficacy. *Aerospace* **8**, 42 (2021).
50. Meinshausen, M. & Nicholls, Z. GWP* is a model, not a metric. *Environ. Res. Lett.* **17**, e041002 (2022).
51. Righi, M., Hendricks, J., Brinkop, S. & Beer, C. G. Global model simulations on the impacts of aviation-induced aerosol on clouds and climate. *AGU Fall Meet. Abstr.* **2023**, A31D–2419 (2023).
52. Fuglestvedt, J., Lund, M. T., Kallbekken, S., Samset, B. H. & Lee, D. S. A "greenhouse gas balance" for aviation in line with the Paris Agreement. *Wiley Interdiscip. Rev. Clim. Change* **14**, e839 (2023).
53. Fuglestvedt, J. S. et al. Transport impacts on atmosphere and climate: Metrics. *Atmos. Environ.* **44**, 4648–4677 (2010).
54. Megill, L., Deck, K. & Grewe, V. Alternative climate metrics to the global warming potential are more suitable for assessing aviation non-CO_2 effects. *Commun. Earth Environ.* **5**, 249 (2024).
55. Borella, A. et al. The importance of an informed choice of CO2-equivalence metrics for contrail avoidance. *EGUsphere* **2024**, 1–24 (2024).
56. Del Prado, A. et al. Animal board invited review: Opportunities and challenges in using GWP* to report the impact of ruminant livestock on global temperature change. *Animal* **17**, 100790 (2023).
57. United Nations Framework Convention on Climate Change. Paris Agreement https://unfccc.int/sites/default/files/english_paris_agreement.pdf (2015).
58. Masson-Delmotte, V. et al. Summary for policymakers. In *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (Cambridge University Press, 2018).
59. Ström, L. & Gierens, K. First simulations of cryoplane contrails. *J. Geophys. Res. Atmos.* **107**, AAC–2 (2002).
60. Bass, F. M. A new product growth for model consumer durables. *Manag. Sci.* **15**, 215–227 (1969).
61. Jarne, G., Sanchez-Choliz, J. & Fatas-Villafranca, F. "S-shaped" curves in economic growth. A theoretical contribution and an application. *Evolut. Institutional Econ. Rev.* **3**, 239–259 (2007).
62. Kucharavy, D. & De Guio, R. Application of S-shaped curves. *Procedia Eng.* **9**, 559–572 (2011).
63. Kucharavy, D. & De Guio, R. Application of logistic growth curve. *Procedia Eng.* **131**, 280–290 (2015).
64. Ponater, M., Pechtl, S., Sausen, R., Schumann, U. & Hüttig, G. Potential of the cryoplane technology to reduce aircraft climate impact: A state-of-the-art assessment. *Atmos. Environ.* **40**, 6928–6944 (2006).
65. Masson-Delmotte, V. et al. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change (Cambridge University Press, 2021).
66. Cain, M. et al. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *npj Clim. Atmos. Sci.* **2**, 29 (2019).
67. Smith, M., Cain, M. & Allen, M. Further improvement of warming-equivalent emissions calculation. *npj Clim. Atmos. Sci.* **4**, 19 (2021).
68. Forster, P. et al. Changes in atmospheric constituents and in radiative forcing. In *Climate Change 2007 : The Physical Science Basis. Working Group I contribution to the Fourth Assessment Report of the IPCC* (Cambridge University Press, 2007).
69. Shine, K., Fuglestvedt, J., Hailemariam, K. & Stuber, N. Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases. *Clim. Change* **68**, 281–302 (2005).
70. Balcombe, P., Speirs, J. F., Brandon, N. P. & Hawkes, A. D. Methane emissions: choosing the right climate metric and time horizon. *Environ. Sci. Process. Impacts* **20**, 1323–1339 (2018).
71. Stocker, T. F. et al. Technical summary. In *Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2013).

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Sara Arriolabengoa: Conceptualization, Methodology, Validation, Investigation, Visualization, Writing–Original draft. Thomas Planès: Conceptualization, Methodology, Validation, Software, Visualization, Writing–Original draft and Review and Editing. Philippe Mattei: Conceptualization, Methodology, Supervision, Writing–Original draft and Review and Editing. Daniel Cariolle: Conceptualization, Writing–Review and Editing. Scott Delbecq: Software, Writing–Review and Editing

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The authors declare no competing interests.

Additional information

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