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Pathways for including non-carbon dioxide aviation climate effects in the European Emission Trading System

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Aviation emissions are responsible for climate impacts through both carbon dioxide emissions and other emissions, in particular, of nitrogen oxides, water vapour, particulates, and contrail formation. In December 2022, the European Commission, Parliament and Council agreed to revise the European Union Emission Trading System for aviation. As such, from January 1, 2025, aircraft operators must monitor non-carbon dioxide climate effects, but suitable metrics for climate impact, handling of uncertainties and practical implementation are still under discussion or at least heavily debated. In this perspective, we propose a procedure for how to include non-carbon dioxide aviation effects into political frameworks. The main goal must be to create incentives for climate change mitigation for the aviation industry. Uncertainties in atmospheric processes need to be appropriately incorporated to minimise risk, and pilot projects are required to test implementation capabilities. Analysing risk, employing consistent monitoring, and determining economic effects will provide scientific grounds for including non-carbon dioxide effects in the European Union Emission Trading System.

Aviation emits carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_x), particulates (soot, sulphate aerosols) and compounds from incomplete combustion (unburnt hydrocarbons). The emitted species are transported in the atmosphere and alter a wide range of atmospheric processes, including the formation of contrail-cirrus, the generation of ozone and the depletion of methane[1,2]. During mixing of the hot and humid exhaust with the environment, 100% relative humidity with respect to liquid phase water can occur, which leads to the formation of water droplets. They freeze if atmospheric temperatures are below −38 °C. If the ambient relative humidity with respect to ice is at or above 100%, the contrail will persist. Hence, the formation of persistent contrail-cirrus depends on aircraft and fuel parameters that determine the exhaust conditions, as well as atmospheric conditions[3,4]. The likelihood of a contrail forming is largely independent of the emitted particulates. The contrail properties, in contrast, such as the number of ice crystals and contrail lifetime, are dependent on the emissions[5,6]. The emitted nitrogen oxides (NO_x) react with hydroxyl radicals ($HOx = OH + HO_2$) and lead to enhanced ozone formation. During this reaction chain, more OH becomes available, which in turn reacts with atmospheric methane, decreasing its concentration. This induces a negative feedback mechanism on the background ozone production as well as on stratospheric water vapor, since stratospheric methane eventually oxidizes, producing water vapor.

Uncertainties in the estimate of the climate impact of aviation arise from various sources. Although the fuel consumption per flight is well constrained, the distribution of emissions has quite an uncertainty, since, e.g., for NO_x, the thrust settings and atmospheric conditions such as pressure and humidity largely control the amount of emissions. The effects of NO_x emissions on O_3 depend on the transport pathways of the air parcel which might take several weeks[7] and atmospheric background conditions[8] are important, whereas the distance to the tropopause[9–11] is important for the impact of water vapor emissions and the amount of supersaturation with respect to ice, and eventually aerosol load, engine and fuel characteristics and vertical motions (over several hours following formation) are important for contrail-cirrus. The planning of flights that considers the climate impact of non-CO_2 effects requires weather forecast data that entails an uncertainty represented, e.g., by ensemble predictions.

Albeit large uncertainties, the EASA-report to the EU commission[1] that is largely based on the work by Lee et al.[2] pointed out that the "Effective Radiative Forcing (ERF) from the sum of non-CO_2 impacts yields a net warming that accounts for more than half (66%) of the aviation net forcing." This statement has largely been consistent over the past roughly 25 years.

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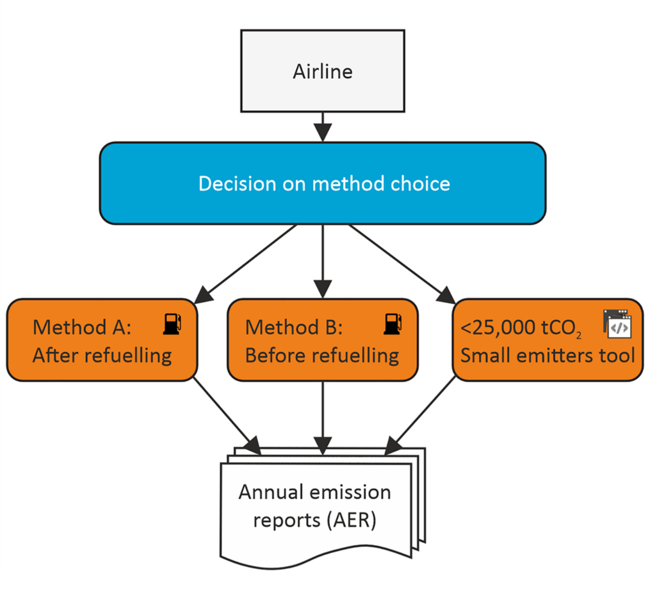
Box 1 | Monitoring of aviation CO2 under the EU ETS

Aircraft operators that have obligations under the EU ETS must monitor CO_2 emissions throughout the year. CO_2 emissions of a flight are estimated by a simplified version of the standard methodology for combustion emissions[49]: the amount of fuel burnt is determined by measuring the remaining fuel in aircraft tanks (before and after the flight) and the refuelled fuel volume, and then multiplied by a constant CO_2 emission index. Two different approaches are allowed, where tank measurement must be performed either after (method A) or before refuelling (method B). In annual emissions reports (AER), CO_2 emissions must be declared separately per aerodrome pair and per country of departure and arrival, but may be aggregated for different aircraft types burning the same fuel. AERs must be prepared after the end of the year, verified by verifiers and the verified report submitted to the Competent Authority. The submitted AER is evaluated according to the approved monitoring plan, which specifies the operator's tasks for data collection, emission calculations and data archiving. For the preparation and evaluation of AERs, Eurocontrol is providing web applications called *ETS Support Facility*[50]. Small operators emitting less than 25,000 t CO_2 per year are also allowed to estimate their fuel consumption via Eurocontrol's EC-approved *Small Emitter Tool*[51].



Already, the IPCC states, "Over the period from 1992 to 2050, the overall radiative forcing by aircraft (excluding that from changes in cirrus clouds) for all scenarios in this report is a factor of 2–4 larger than the forcing by aircraft CO_2 alone."[12] Although the understanding of aviation climate effects has been enhanced extensively from 1999 to 2021, the uncertainty ranges have remained at similar magnitudes. Taking this into account, the Trilogue (The bodies involved in trilogue negotiations are the European Commission, the Council of the European Union, and the European Parliament.) decision is comprehensible, but requires a mechanism to appropriately account for non-CO_2 aviation effects, including uncertainty considerations.

Since 2012, CO_2 emissions from aviation within the European Economic Area have been regulated by the EU emissions trading system (EU-ETS). The EU-ETS is a so-called "cap and trade scheme". In the EU-ETS, the total amount of CO_2 of the emitters subject to the scheme is fixed and must not be exceeded. Aircraft operators, as well as other companies under the scheme (such as energy-intensive industries, for instance), are required to hold permits for each ton of CO_2 emitted. Emitters who reduce their emissions can sell excess permits to others, creating a financial incentive to lower emissions. The cap and the cost for CO_2 abatement determine the price of permits, incentivizing cost-effective emission reductions. As air transport faces relatively high CO_2 abatement costs as compared to the other sectors under the trading scheme, in most cases, aviation is a net buyer of European Emission Allowances.

Initially, the emissions cap for aviation was set at 95% of the average ETS-relevant CO_2 emissions from 2004 to 2006, a level that was maintained until 2020. Since 2021, the cap has been decreasing by 2.2% annually, resulting in a reduction of total emissions. This reduction rate will increase to 4.3% annually from 2024 and to 4.4% annually from 2028. If non-CO_2 aviation effects are included in the EU-ETS, aircraft operators will be required to hold more permits for climate-intensive flights, such as those with strongly warming contrails. To reduce their CO_2 equivalent emissions and associated costs, aircraft operators can adopt cleaner technologies and operations. This also encourages innovation and efficiency. Facing higher costs, aircraft operators are motivated to invest in research and development, such as more efficient aircraft and engine options, sustainable aviation fuels, and climate-optimized routings.

Here, we propose to start with a set of calculation methods that allow the estimation of the climate impact of single flights[13–15] with varying degrees of complexity and use the results of this calculation method as input to an appropriate climate metric to convert the non-CO_2 effects into equivalent CO_2 emissions. Note that for individual flights the total climate impact (CO_2 plus non-CO_2 effects) might differ greatly from a constant value for various reasons: (1) The use of sustainable alternative fuels reduces the CO_2 contribution and contrail formation, (2) different engine technologies might reduce contrail (via particulate emission) and NO_x impacts more than CO_2[16], (3) flights in different geographical regions might have very different weightings between the individual non-CO_2 effects (e.g., ozone impacts are larger in the tropics[17]), and (4) different flight altitudes have substantially different weights for non-CO_2 effects[18–21].

Calculating equivalent CO_2 emissions for non-CO_2 aviation climate effects

This inclusion of non-CO_2 aviation climate effects requires a method to convert those into equivalent CO_2 emissions that can be traded. Those methods use the three-dimensionality of the atmosphere to represent atmospheric responses and a climate metric, and they depict a trade-off between the level of atmospheric uncertainties, the level of climate mitigation incentives, and the resulting effort of monitoring, reporting and verification. For aviation, CO_2 emissions are reported to the EU-ETS (Box 1), allowing different methods to calculate them, but in principle allowing the extension to non-CO_2 effects. However, a CO_2e estimation system requires additional data (e.g., aircraft and engine information, flight trajectories, emission estimates, meteorology, fuel properties) for monitoring and reporting by aircraft operators, for verification by an independent third party (i.e., accredited verification bodies) and for emission report approval by the state competent authority. Note that the choice of a climate metric that has to be made for converting non-CO_2 effects into equivalent CO_2 emissions applies equally to all of the calculation methods discussed here (see below for further discussions). Several CO_2e calculation methods are available (see Box 2), and their selection process involves this trade-off. The higher the accuracy of estimates of relevant atmospheric processes, the more efficient the incentives for climate mitigation. However, more accurate CO_2e approaches will also require a higher amount of data for monitoring, reporting and verification.

Key criteria (but not the only, see e.g., Megill et al.)[22] for choosing a CO_2e calculation method that include both the atmospheric response and a climate metric are therefore:

CO_2e must provide incentives for actual mitigation and reducing non-CO_2 effects *(not simply adding costs, but providing the possibility to reduce climate impact and cost of operation)*
CO_2e should be easily calculable, predictable and transparent

Analogous to the CO_2 monitoring in EU-ETS and under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), different CO_2e calculation methods can be made available (e.g., climatological and weather-based approaches for climate response simulations).

In contrast to CO_2, non-CO_2 effects are largely dependent on the location and time of emission[14,15,18,19,23,24]. Without the knowledge of flight time and flight trajectory, an averaged climatological equivalent CO_2 emission can be calculated. The more detailed information available on flight time and flight trajectory, the more detailed calculations of equivalent CO_2 emissions can be provided. Eventually, those are weather as well as space and time dependent (Box 2). Between the easiest calculation method, which is a simple constant factor applied to the CO_2 emissions to obtain equivalent CO_2 emissions and the most complex weather-dependent and hence temporally and spatially varying factors, various possibilities exist. The calculated equivalent CO_2 emissions are more relevant and have more benefits if more processes are considered (going down the chain in Box 2), but the amount of data and the effort to calculate the equivalent CO_2 emissions may increase.

The calculation of equivalent CO_2 emissions requires a physical climate metric to convert individual emissions into a relevant climate indicator[25,26] and to appropriately consider the varying timescales on which the individual processes act. Climate metrics have three basic components: (i) the temporal emissions, like pulse, sustained or scenario emissions, (ii) the climate indicator, like mean radiation change, temperature or mean temperature change, and (iii) the time horizon. For a specific application, not all combinations are meaningful[27]. Note that the metric choice often may constitute a minor source of uncertainty, in particular when the choice is between an integrative measure like GWP versus a point metric like GTP, or for large variations in the time horizon, say 20–100 years[28,29]. Requirements were broadly discussed in the literature and address, e.g., fairness[30], simplicity and consistency with current policy[29,31]. Megill et al.[22] especially pointed out that the climate assessment of an aviation technology by using a climate metric should be consistent with a corresponding whole scenario assessment, and they tested climate metrics against requirements for a large set of aviation-related applications, allowing the identification of suitable climate metrics.

Examples of more simplified calculation methods are given in Dahlmann et al.[13], who analyzed data of more than 1000 flights with an A330-200[32] and included estimates of the climate impact of each flight. More detailed calculations require tools that consider aircraft and fuel characteristics and atmospheric data either in a climatological manner[23,33] or weather-related[34,35]. In any case, simple constant factors must not be used since they do not allow for a reduction of non-CO_2 effects, instead concentrating on CO_2 only.

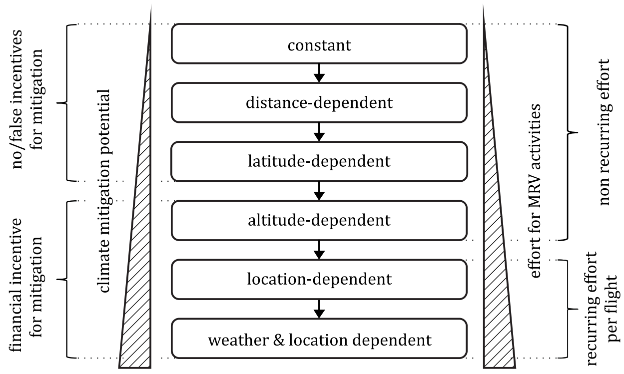
Therefore, the calculation of equivalent CO_2 emissions that include the non-CO_2 effects is technically feasible.

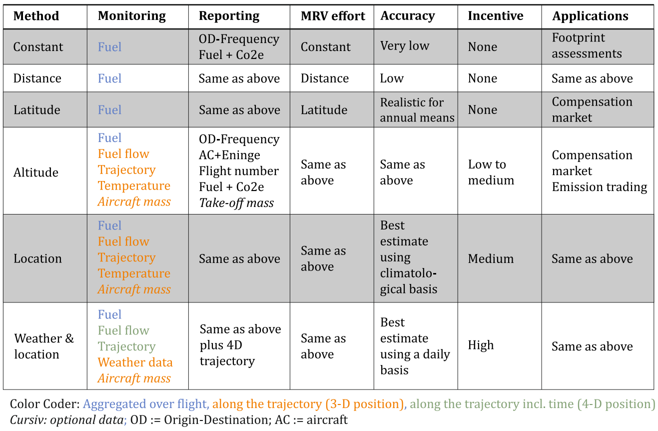
Box 2 | Calculating CO_2 equivalent emissions (CO_2e) for non-CO_2 aviation effects

For the calculation of equivalent CO_2 emissions, a variety of methods are available that differ in the degree of detail (right, increasing from top to bottom) and have effects on the climate mitigation potential and the effort necessary for the MRV activities. A **constant factor** that simply multiplies CO_2 emissions, a varying factor that only depends on the **distance** or **latitude,** is based on climatological CO_2e calculations that include information about the route. They are all, in principle, simple variations of a constant factor and may be used for ecological footprint assessments. **Altitude** and **location-**dependent methods may also include information on the technology (e.g., detailed NO*x* emissions), and eventually, **weather and location-**dependent methods that take the full information of the weather and flightpath into account have a large climate mitigation potential and set in principle a good incentive for aviation climate mitigation. The latter two differ by the degree of detail in which weather information is taken into account.

Constant factors are heavily criticized and proven to be inappropriate since they further increase the focus on CO_2 reduction, might create false incentives (incentive to fly higher rather than lower) and "penalize" climate-cost-efficient routings (due to the increased fuel burn)[13,52,53]. In order to avoid misguiding incentives, at least the altitude dependency of non-CO_2 effects has to be considered in the CO_2e calculation method[53,54]. This requires at least detailed information about the aircraft flightpath (altitude profile).

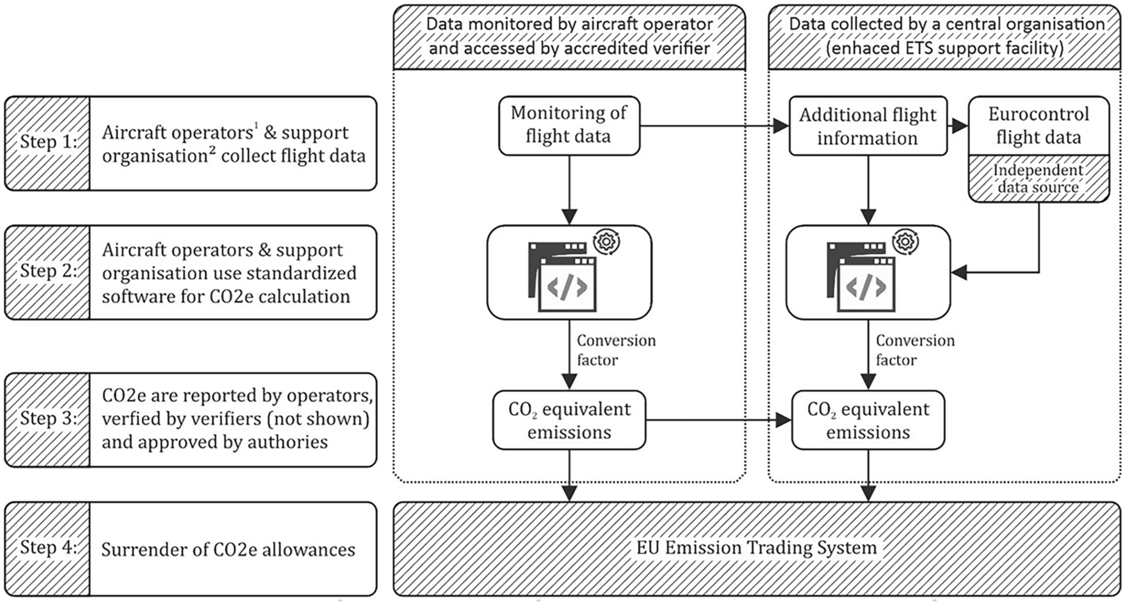
The location-dependent method relies on climatological mean data (evaluated over the annual or seasonal means). In this case, the CO_2e value is estimated individually for each flight, regardless of the actual weather. If an aircraft flies the same 3D flight profile on the same route every day, the estimated CO_2e level remains identical. As a result, the climate impact of a single flight might be over- or underestimated for individual weather situations. However, the route-specific CO_2e estimate of all flights over the reference period (e.g., year, season) is reasonably accurate, as weather variations of single days are balanced.





Method	Monitoring	Reporting	MRV effort	Accuracy	Incentive	Applications
Constant	Fuel	OD-Frequency Fuel + Co2e	Constant	Very low	None	Footprint assessments
Distance	Fuel	Same as above	Distance	Low	None	Same as above
Latitude	Fuel	Same as above	Latitude	Realistic for annual means	None	Compensation market
Altitude	Fuel Fuel flow Trajectory Temperature *Aircraft mass*	OD-Frequency AC+Eninge Flight number Fuel + Co2e *Take-off mass*	Same as above	Same as above	Low to medium	Compensation market Emission trading
Location	Fuel Fuel flow Trajectory Temperature *Aircraft mass*	Same as above	Same as above	Best estimate using climatological basis	Medium	Same as above
Weather & location	Fuel Fuel flow Trajectory Weather data *Aircraft mass*	Same as above plus 4D trajectory	Same as above	Best estimate using a daily basis	High	Same as above

Color Coder: Aggregated over flight, along the trajectory (3-D position), along the trajectory incl. time (4-D position)
Cursiv: optional data; OD := Origin-Destination; AC := aircraft



^{1}Airlines collect flight data for all flights

^{2}Central support organisation collect data from different 3rd party independent sources for simplified reporting and CO2e approval

Fig. 1 | Monitoring, reporting and verification steps for integrating non-CO_2 aviation effects into the EU-ETS. The four steps include the collection of data, calculation of CO_2e, and the reporting and surrender of allowances by aircraft operators. A central support organization collects conservative data estimates from independent data sources for simplified reporting and CO_2e approval (adapted from Plohr et al.[55], 2023).

The implementation of an MRV system for non-CO_2 effects

We suggest that an implementation of the calculation of equivalent CO_2 emissions is based on two physics-based models for the estimate of emissions and climate effects, including uncertainties, and a policy-based module that integrates political decisions, e.g., concerning uncertainties, weightings, and metrics.

Since all CO_2e calculation methods that allow incentives to reduce the climate impact of single flights require additional data, the aircraft operator has first to record flight data (step 1 in Fig. 1) and second to calculate CO_2 equivalent emissions per flight (step 2 in Fig. 1). In order to reduce the additional MRV effort to a minimum, all necessary CO_2e calculation steps should automatically be performed by a standardized CO_2e software (see Fig. 1 and Box 3), possibly provided directly by the European Commission or by an approved organization. CO_2e reporting should be limited to the most important data necessary for CO_2e report approval. To enable simplified CO_2e reporting (e.g., for small emitters) with conservative prefilled figures, a centralized support organization should collect relevant information from independent sources, such as flown flight profiles by Eurocontrol, meteorological data by weather services. Here, attention has to be put on consistency in monitored and third-party data to assure comparable results for CO_2e report approval. Additional aircraft properties and performance data (such as, e.g., fuel flow) can optionally be uploaded to the secondary data repository to improve accuracy, thereby also reducing the need for conservative estimation of particular data needed for CO_2e computation.

The more detailed the CO_2e approach, the more data is needed for the implementation of an MRV system. The higher the accuracy of modeling the relevant atmospheric processes, the greater the climate mitigation impact that is achievable. Note also that possibilities may have to be established to integrate aspects such as novel aircraft fuels or new propulsion technologies when they are operationally implemented.

Therefore, the split into physics-based and policy-based modules allows for a clear separation of the current state of atmospheric science and political developments.

On the inclusion of uncertainties in the MRV system

To better understand the impact of uncertainties on the calculation of non-CO_2 effects and thereby on the potential of setting wrong incentives, risk assessments are required and should be included in the implemented software. This allows, e.g., a weighting of non-CO_2 effects according to the uncertainty or risk. First, the climate mitigation potentials of specific strategies that result from spatial and temporal atmospheric sensitivities have to be verified, the quality of CO_2e estimates assessed, and risks deduced, e.g., by combinations of flight tests with observational data and modeling approaches (see also below). Second, reported CO_2e values have to represent the estimated climate impact of aviation on average and by that, consistency between different accounting methods can be achieved. This requires a solid database, including flight information, fuel consumption, as well as CO_2e from numerous flights. Necessary data could be collected in the pilot non-CO_2 MRV system of the EU-ETS starting in 2025, in which non-CO_2 effects are already monitored and reported, but are not yet subject to monetary internalization.

As described in Lee et al.[2] and briefly summarized above, various aspects are sources of fairly large uncertainties in CO_2e calculation. Some processes might even have to be addressed at a later stage where the scientific understanding is currently not mature enough to be included in an MRV system, such as the impact of sulphate aerosols on low-level clouds and soot emissions on cirrus[36,37]. Note that for giving the right incentives to minimize the climate impact of aviation, not only the absolute values of the non-CO_2 effects are needed. Instead, their sensitivities and spatial variations and gradients are more important to be captured. While the uncertainty in the absolute value of the non-CO_2 effects is large[2], there is quite some agreement in the vertical sensitivity and impacts from flight altitude changes among models[21].

Uncertainties can also be used to assess their impact on decisions. Despite large uncertainties in the climate impact assessment of an aircraft design, the variations to routings and designs can be assessed with higher fidelity[32]. Here, we used Lee et al.'s[2] description of the probability density functions to estimate the likelihood that CO_2 ERF contributes around 20–40% to the total ERF. We find that the probability is 70% and the risk that CO_2 ERF is even larger than non-CO_2 effects is 12%, only (Fig. 2). This

Box 3 | Set-up of the required software for CO_2e calculations per flight

For CO_2e monitoring (see step 2 from Fig. 1), we suggest that the software should include two physics-based and one policy-based simulation steps (module):

1st physics-based module:

An emission module for the estimation of CO_2, H_2O and NO_x, particulate emissions along the flight path.

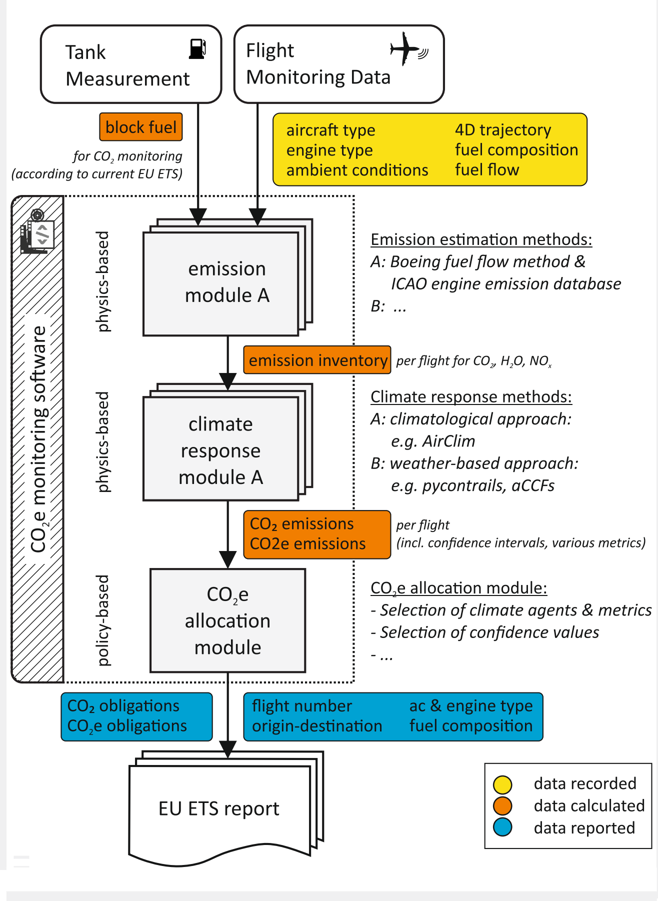
2nd physics-based module:

A climate response module for the CO_2e estimation of H_2O, NO_x and contrails, including a measure for the uncertainties (e.g. 5% percentile, 50% percentile, 95% percentile) for the selected climate indicators and time horizons (20, 50, 100 years), depending on the authority's decision.

Policy-based module:

Based on the political decision on how to eventually set up the EU-ETS, the information from the climate module is selected and processed to calculate the CO_2e.

Analogous to the CO2 monitoring in the EU ETS and under CORSIA, different calculation methods can be made available for these physics-based modules (e.g., climatological and weather-based approaches for climate response simulations, see Box 2). The selection of the calculation methods (possibly aircraft type- or city pair-specific) should be specified in the operator-specific Emission Monitoring Plan (EMP) and submitted to the competent authority for approval. Following the physical-based modules, the EU decision is implemented in a policy-based module in order to set the level of CO_2e obligations (e.g., depending on the confidence levels of each climate agent).



exemplifies how uncertainties in the climate impact assessment can be used to assess the risk of wrong statements and decisions. Recently, those uncertainties in global mean values were analyzed with regard to their associated risk in climate mitigation strategies[38]. However, we do not support their approach to simply assume the uncertainties from Lee et al.[2] evenly over all flights, as it entirely lacks consideration of flight-to-flight variability and related influences of different uncertainty sources.

With respect to the implementation of non-CO_2 effects in an MRV system, there are two important aspects of risks that have to be carefully considered: (1) the risk of enhancing the climate impact instead of reducing it and (2) how to integrate a risk treatment in the MRV system. It is often communicated that it is very likely that the non-CO_2 ERF is larger than the CO_2 ERF. Figure 2 explores the risk that this statement is wrong. Similarly, an analysis of the risk that using a specific CO_2e calculation method offers an incentive to falsely increase the climate impact on an annual basis should be assessed. Note that it might be well accepted that individual flights may occasionally be misguided due to the calculation method increasing the overall climate impact, as long as the majority of flights reduce the overall climate impact on an annual basis at a low risk. However, the acceptance level has to be discussed.

The 3-step process (Box 3) for an MRV system might include, as a last step, a more politically-based CO_2e assignment tool using the provided information from the 2nd physics-based model that might encompass CO_2e for different time horizons, for atmospheric processes not yet considered and uncertainties and translates it according to implemented rules into the final CO_2e. The uncertainties might be used to assess the risk of failure in reducing the climate impact, or different weightings of CO_2e could then be derived. Hence, for large uncertainties in the estimate of individual non-CO_2 effects, those uncertainties might only be included in the CO_2e calculation with a low weight or even be disregarded. Exemplarily, Fig. 2 (right) gives the enhancement of the aviation CO_2 ERF value due to non-CO_2 effects as a probability density function. The median value of this enhancement factor is 2.88, but due to the large uncertainty, there would also be the possibility of using the lower bound of a confidence interval of 1.56 (brown). For individual fights, the uncertainty ranges might be much larger, and trade-offs between CO_2 and non-CO_2 contributions to CO_2e could also be limited, i.e., by introducing a lower bound of such an enhancement factor. This uncertainty consideration refers to its inclusion in the CO_2e calculation, whereas mitigation might include the uncertainty in weather forecasts, additionally. For this, probabilistic route optimization might also enforce robust trajectory calculations[39].

Overall, assessing in detail all uncertainties connected with CO_2e calculation and integrating them in the framework can help maximize confidence in the estimations and minimize the risks in climate mitigation actions, as well as in setting incentives for them. Therefore, we consider the integration of confidence levels into the CO_2e calculation as a necessary step to overcome negative implications due to the large uncertainties in non-CO_2 aviation effects, as discussed in literature[40].

Economic aspects of regulating air transport's CO_2 and non-CO_2 emissions

The integration of non-CO_2 emissions in the EU-ETS requires, from the perspective of economic efficiency and equal treatment of aircraft operators operating in the regulated European airspace, an equal treatment of all aircraft operators by the MRV regulatory framework. This is regardless of dependencies on operational specifics of individual aircraft operators or types of aircraft operators, like e.g., destinations, rotations and planned flight times. This should create a level playing field for all aircraft operators under the system. Moreover, as aviation is an international business, the competitive position of European aircraft operators that predominantly fly in Europe compared to other aircraft operators that predominantly fly outside the EU-ETS airspace should be supported, such that a level playing field in the global air transportation sector will be created. Otherwise, CO_2 and non-CO_2 leakage and economic disadvantages for the European aircraft operators are likely. Especially re-routings to fully or partly avoid the

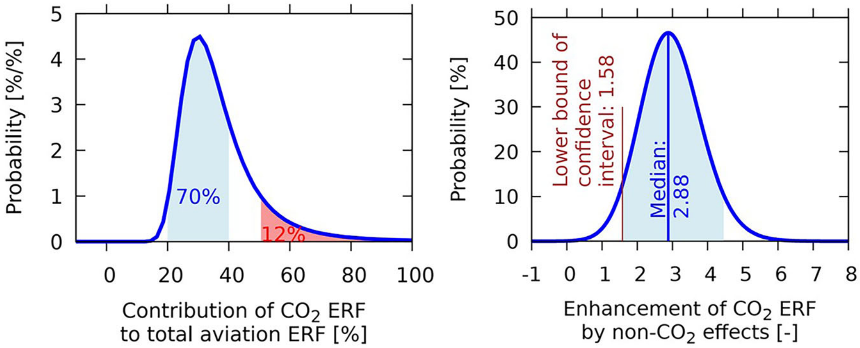


Fig. 2 | Example for a risk assessment and the underlying uncertainty information. Left: Probability density function of the ratio of the CO_2 ERF to the total aviation-induced ERF. The PDF for the CO_2 ERF is estimated by a normal distribution $N(34.5,3.56)$ and the total by $N(100.9,27.54)$. The area under the graph between 20% and 40% indicates its probability, which is 70% and the tail for values above 50% is 12%. Right: Probability density function of the ratio of the total aviation-induced ERF to the CO_2 ERF, i.e., a CO_2 enhancement factor. The 90% confidence interval is shaded light blue, with the lower bound indicated in brown. Data are based on Lee et al.[2].

financial obligations of the EU-ETS to geographically relatively close hubs, such as Istanbul and the UAE airports, seem promising from an economic point of view. However, this could lead to a relocation of climate-relevant emissions from these flights, which should be avoided.

The aviation market is exposed to a large number of economic uncertainties, such as unforeseeable developments in the price of crude oil in the future. Furthermore, there are a great number of charges and fees, such as take-off and landing fees, ATC fees and national charges, which have to be paid in order to be able to operate as an aircraft operator in Europe at all. In addition, air transport's CO_2 compliance costs under the EU-ETS are rising predominantly, as of October 2023, about 80€ per ton of CO_2[41]. If the non-CO_2 species of aviation will be included in the EU-ETS in the future, compliance costs can be expected that will be twice or three times as large as the CO_2 costs today in case these climate-relevant emissions cannot be mitigated[42]. For this reason, in order to guarantee a level playing field in this global sector, it is expected that financial compensation for aircraft operators regulated by the EU-ETS will be necessary.

Against this background, the goal of an EU-ETS supplemented by non-CO_2 species should be to allow both environmental effectiveness and economic efficiency. It is desirable that additional financial obligations from the EU-ETS or from mitigation measures are designed in such a way that these measures, such as alternative routing to avoid non-CO_2 emissions, do not cause disproportionately high costs compared to the status quo.

Required research in support of the MRV

Hence, the way to integrate non-CO_2 climate effects from aviation in the European Emission Trading System is certainly challenging, but there is a clear roadmap to overcome potential obstacles. A key step is the provision of calculation methods to obtain CO_2e estimates for individual flights. Key points that have to be clarified are

Determination of the risk of wrong decisions: Consider, for example, a re-routing option, like avoiding contrail formation regions to a certain degree during a whole year. The probability that this strategy increases the climate impact instead of decreasing it is an important quantity that allows robust decisions. The considered total uncertainties may include specific uncertainties from forecasting capabilities, description of ISSR-regions, or contrail development aspects influencing its radiative properties.

Consistency of models: Individual methods for calculating CO_2e on an annual basis should be consistent. Aircraft operators may be able to choose individual steps of the calculation method, and that should not lead to benefits; fairness is key here. Note that comparable choices are already part of the ETS for the CO_2 reporting (see Box 1), and similar consistency checks were performed for CO_2 accounting.

Validation and verification of methods: Weather-related approaches allow for the use of satellite data in order to evaluate contrail-related strategies[43]. For other species, this might not be feasible, and more consistency checks might have to replace validation assessments[44,45].

Fair market: Financial compensation might be considered to address those aircraft operators that fall under the non-CO_2 regulations, so that a level playing field remains on the global market.

In any case, the increasing number of pilot projects[46–48] that are currently performed is necessary to enable further developments of weather models to include the prediction of non-CO_2 climate effects, to learn how data management can be optimized, and to understand what consequences the climate-optimized routing has on daily procedures for dispatchers, air traffic service providers, aircraft operators, etc. Economic consequences and potential misuses have to be addressed and understood. However, uncertainties in climate science (as well as in other aspects of CO_2e calculations) are not necessarily a showstopper for a regulatory MRV, but need to be addressed by appropriate validation and verification as well as by risk assessments. Skillful use of uncertainties can minimize risk and maximize confidence in climate mitigation actions and in setting incentives for them.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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References

1. EASA, Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4), COMMISSION STAFF WORKING DOCUMENT, Accompanying the document Report from the Commission to the European Parliament and the Council, {COM(2020) 747 final. (eds Arrowsmith et al.) Brussels, 23 November 2020. https://www.easa.europa.eu/sites/default/files/dfu/201119_report_com_ep_council_updated_analysis_non_co2_climate_impacts_aviation.pdf (2020).
2. Lee, D. S. et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Env.* https://doi.org/10.1016/j.atmosenv.2020.117834 (2021).
3. Schmidt, E. Die Entstehung von Eisnebel aus den Auspuffgasen von Flugmotoren. in: *Schriften der deutschen Akademie der Luftfahrtforschung*. Heft 44, pp 1–15 (Verlag R. Oldenbourg, München, 1941).
4. Appleman, H. The formation of exhaust condensation trails by jet engines. *Bull. Am. Meteorol. Soc.* **34**, 14–20 (1953).
5. Voigt, C. et al. Cleaner burning aviation fuels can reduce contrail cloudiness. *Commun. Earth Env.* **2**, 114 (2021).
6. 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).

7. Rosanka, S., Frömming, C. & Grewe, V. The impact of weather pattern and related transport processes on aviation's contribution to ozone and methane concentrations from NOx emissions. *Atmos. Chem. Phys.* **20**, 12347–12361 (2020).
8. Skowron, A. et al. Greater fuel efficiency is potentially preferable to reducing NOx emissions for aviation's climate impacts. *Nat. Commun.* **12**, 564 (2021).
9. Wilcox, L., Shine, K. P., Hoskins, B. J. Radiative forcing due to aviation water vapour emissions. *Atmos. Env.* https://doi.org/10.1016/j.atmosenv.2012.08.072 (2012).
10. Frömming, C. et al. Influence of the weather situation on non-CO2 aviation climate effects: the REACT4C climate change functions. *Atmos. Chem. Phys.* **21**, 9151–9172 (2021).
11. van Manen, J. & Grewe, V. Algorithmic climate change functions for the use in eco-efficient flight planning. *Transp. Res. Part D* **67**, 388–405 (2019).
12. Intergovernmental Panel on Climate Change (IPCC): Special report on aviation and the global atmosphere. (eds Penner, J. E., Lister, D. H., Griggs, D. J., Dokken, D. J. & McFarland, M.) (Cambridge University Press, New York, NY, USA, 1999).
13. Dahlmann, K., Matthes, S., Yamashita, H. & Grewe, V. Climate assessment of single flights: deduction of route specific equivalent CO_2 emissions. *Int. J. Sustain. Transp.* **17**, 29–4 (2023).
14. Grewe, V. et al. Reduction of the air traffic's contribution to climate change: a REACT4C case study. *Atmos. Env.* **94**, 616–625 (2014).
15. Matthes, S. et al. Climate optimized air transport. (eds Schumann, U.) ISBN 978-3-642-30182-7, ISBN 978-3-642-30183-4 (eBook). (Springer, Heidelberg, New York, Dordrecht, London, 2012).https://doi.org/10.1007/978-3-642-30183-4. pp 727–746.
16. Grewe, V. et al. Assessing the climate impact of the AHEAD multi-fuel blended wing body. *Met. Z.* **26**, 711–725 (2017).
17. Köhler, M. O., Rädel, G., Shine, K. P., Rogers, H. L. & Pyle, J. A. Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics. *Atmos. Env.* **64**, 1–9 (2013).
18. Köhler, M. O. et al. Impact of perturbations to nitrogen oxide emissions from global aviation. *J. Geophys. Res.* **113**, D11305 (2008).
19. Rädel, G. & Shine, K. P. Radiative forcing by persistent contrails and its dependence on cruise altitudes. *J. Geophys. Res.* **113**, D07105 (2008).
20. Frömming, C. et al. Aviation-induced radiative forcing and surface temperature change in dependency of the emission altitude. *J. Geophys. Res.* **117**, D19 (2012).
21. Matthes, S. et al. Mitigation of non-CO2 aviation's climate impact by changing cruise altitudes. *Aerospace* **8**, 36 (2021).
22. Megill, L., Deck, K. & Grewe, V. Alternative climate metrics to the global warming potential are more suitable for assessing aviation non-CO2 effects. *Commun. Earth Env.* **5**, 249 (2024).
23. Grewe, V. & Stenke, A. AirClim: an efficient climate impact assessment tool. *Atmos. Chem. Phys.* **8**, 4621–4639 (2008).
24. 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).
25. Fuglestvedt, J. S. et al. Transport impacts on atmosphere and climate: Metrics. *Atmos. Env.* **44**, 4648–4677 (2010).
26. Peters, G. P., Aamaas, B., Berntsen, T. & Fuglestvedt, J. S. The integrated global temperature change potential (iGTP) and relationships between emission metrics. *Environ. Res. Lett.* **6**, 044021 (2011).
27. Grewe, V. & Dahlmann, K. How ambiguous are climate metrics? And are we prepared to assess and compare the climate impact of new air traffic technologies? *Atmos. Env.* **106**, 373–374 (2015).
28. Azar, C. & Johansson, D. J. A. On the relationship between metrics to compare greenhouse gases – the case of IGTP, GWP and SGTP. *Earth Syst. Dyn.* **3**, 139–147 (2012).
29. Borella, A. et al. The importance of an informed choice of CO_2-equivalence metrics for contrail avoidance. *Atmos. Chem. Phys.* **24**, 9401–9417 (2024).
30. Rogelj, J. & Schleussner, C. F. Unintentional unfairness when applying new greenhouse gas emissions metrics at country level. *Environ. Res. Lett.* **14**, 114039 (2019).
31. Meinshausen, M. & Nicholls, Z. GWP*is a model, not a metric. *Environ. Res. Lett.* **17**, 041002 (2022).
32. Dahlmann, K. et al. Climate-compatible air transport system—climate impact mitigation potential for actual and future aircraft. *Aerospace* **3**, 38 (2016).
33. Dahlmann, K., Grewe, V., Frömming, C. & Burkhardt, U. Can we reliably assess climate mitigation options for air traffic scenarios despite large uncertainties in atmospheric processes? *Trans. Res. Part D* **46**, 40–55 (2016).
34. Dietmüller, S. et al. A Python library for computing individual and merged non-CO2 algorithmic climate change functions: CLIMaCCF V1.0. *Geosci. Model Dev.* **16**, 4405–4425 (2023).
35. Teoh, R. et al. Global aviation contrail climate effects from 2019 to 2021. *Atmos. Chem. Phys.* **24**, 6071–6093 (2024).
36. Righi, M., Hendricks, J. & Sausen, R. The global impact of the transport sectors on atmospheric aerosol in 2030—Part 2: aviation. *Atmos. Chem. Phys.* **16**, 4481–4495 (2016).
37. Righi, M., Hendricks, J. & Beer, C. G. Exploring the uncertainties in the aviation soot–cirrus effect. *Atmos. Chem. Phys.* **21**, 17267–17289 (2021).
38. Prather, M. J., Gettelman, A. & Penner, J. E. Trade-offs in aviation impacts on climate favour non-CO_2 mitigation. *Nature* **643**, 988–993 (2025).
39. Simorgh, A. et al. Robust 4D climate-optimal flight planning in structured airspace using parallelized simulation on GPUs: ROOST V1.0. *Geosci. Model Dev.* **16**, 3723–3748 (2023).
40. Lee, D. S. et al. Uncertainties in mitigating aviation non-CO2 emissions for climate and air quality using hydrocarbon fuels. *Environ. Sci.* https://doi.org/10.1039/d3ea00091e (2023).
41. https://www.eex.com/de/maerkte/umweltprodukte/eu-ets-auktionen. Last accessed 9 January 2026.
42. Scheelhaase, J. How to regulate aviation's full climate impact as intended by the EU Council from 2020 onwards. *J. Air Transp. Manag.* **75**, 68–74 (2019).
43. Sausen, R. et al. Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world? *Meteorologische Zeitschrift* **33**, 83–98 (2024).
44. Rao, P. et al. Case study for testing the validity of NOx-ozone algorithmic climate change functions for optimising flight trajectories. *Aerospace* https://doi.org/10.3390/aerospace9050231 (2022).
45. Yin, F. et al. Predicting the climate impact of aviation for en-route emissions: the algorithmic climate change function submodel ACCF 1.0 of EMAC 2.53. *Geosci. Model Dev.* **16**, 3313–3334 (2023).
46. https://www.dwd.de/DE/fachnutzer/luftfahrt/download/produkte/luftfahrt_und_klima/d_kult_info.pdf;jsessionid=FF5F71E63FD403C0AE125545C58E52B8.live31092?__blob=publicationFile&v=1. Last accessed 9 January 2026.
47. https://www.haw-hamburg.de/detail/news/news/show/climate-optimized-flight-routes-the-path-from-research-to-operations/. Last accessed 9 January 2026.
48. https://news.aa.com/news/news-details/2023/American-Airlines-participates-in-first-of-its-kind-research-on-contrail-avoidance-CORP-OTH-08/default.aspx. Last accessed 9 January 2026.
49. European Commission: EU ETS Monitoring and Reporting—Quick guide for aircraft operators. Updated for EU ETS Phase 4—Version of 1 March 2022. https://ec.europa.eu/clima/system/files/2022-03/quick_guide_ao_en.pdf. Accessed on 26 August 2023 (2022).

50. Eurocontrol: Emissions Trading System Support Facility. https://www.eurocontrol.int/service/emissions-trading-system-support. Accessed on 26 August 2023 (2023a).
51. Eurocontrol: Small emitters tool. https://www.eurocontrol.int/tool/small-emitters-tool. Accessed on 26 August 2023 (2023b).
52. Forster, P. M., de, F., Shine, K. P. & Stuber, N. It is premature to include non-CO2 effects of aviation in emission trading schemes. *Atmos. Env.* **40**, 1117–1121 (2006).
53. Niklaß, M. et al. Integration of Non-CO_2 Effects of Aviation in the EU ETS and Under CORSIA, Climate Change, 20, Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/integration-of-non-co2-effects-of-aviation-in-the (2020).
54. Faber, J. et al. *Lower NOx at Higher Altitudes. Policies to Reduce the Climate Impact of Aviation NOx Emission, CE-Delft 08.7536.32, Commissioned by: European Commission, DG Energy and Transport under contract TREN/07/F3/S07.78699.* (Delft, 2008).
55. Plohr, M., Dahlmann, K., Niklaß, M. Testing of a monitoring and reporting scheme for integrating non-CO2 aviation effects into EU ETS, Climate Change, Umweltbundesamt. https://www.umweltbundesamt.de/system/files/medien/11850/publikationen/25_2024_cc_testing_of_a_monitoring.pdf (2024).

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Author contributions

All authors jointly conceived the idea of the paper. V.G. and M.N. wrote most of the initial draft, and A.L. and J.S. complemented the economic considerations to the draft. V.G. performed the calculations for the uncertainty and risk analysis. V.G., M.N., K.D., R.E., S.M., A.L., J.S., F.L., and M.P. reviewed and edited the paper and contributed to the discussion and interpretation, and revised the paper.

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