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Trade-off and risk in mitigation options for aviation

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Abstract. A recently proposed method to statistically treat trade-offs and associated risks in aviation mitigation options (Prather et al., 2025) leaves, to this author's opinion, issues open for discussion. In particular, the method lacks a rigorous mathematical derivation and gives no precise mathematical definition of the central notion "trade-off ratio". The derivation, which is given here, leads to an inequality that expresses the postulate that the total (summed-up) metric value, after a mitigation measure has been taken, must be smaller than the value of the same metric without mitigation. Surprisingly, neither the metric pair itself nor the basic (effective) radiative forcings appear in the inequality. However, if one enforces their presence or if one does not cancel them out like in the original method, uncertain quantities appear on both sides of the inequality, which renders it inadequate for its purpose. In contrast, the method in its "sensitivity form" may work in hindcast mode (that is, to estimate the probability whether a mitigation method was successful), if the changes of the effective radiative forcings due to the measure taken can be determined with sufficient precision, using a climate model with well defined weather patterns over the course of a year or longer.

1 Introduction

In order to lessen aviation's climate impacts, a number of mitigation strategies have been proposed that require developments in technology, operations, and fuel type (e.g. Sausen et al., 1994; Williams et al., 2002, 2003; Mannstein et al., 2005; Ponater et al., 2006; Dahlmann et al., 2016; Matthes et al., 2021; Burkhardt et al., 2018; Teoh et al., 2020; Sausen et al., 2024; Märkl et al., 2024; Noppel and Singh, 2007; Haglind, 2008; Pouzolz et al., 2021). However, the climate impact of aviation has many interdependent components and, unfortunately, lessening one kind of impact may (and often does) increase another one (e.g. Lee et al., 2012, 2023). Trade-offs are often inherent in mitigation if the considered system is complex, like aviation and its climate impact is. To oversee the consequences of any measure can turn out difficult because of the system complexity, but the difficulties in aviation are aggravated by the simultaneous emission of short-lived climate forcers and CO_2. Emitted nitrogen oxides undergo non-linear chemistry in the atmosphere, which implies that the corresponding climate impact depends on the actual background concentration of species which may be dominated from emissions (or sources and sinks) that are not related to aviation at all (Skowron et al., 2021). It is possible that a mitigation measure that is beneficial on a short time horizon will turn out negative for climate on the long run, which evidently impacts any risk assessment. Furthermore, the (effective) radiative forcings of the different aircraft emissions are not known exactly; to the contrary, they are quite uncertain (e.g. Lee et al., 2021). Whether a certain mitigation measure will turn out positive for climate, that is, whether the net climate impact will be reduced, is thus a difficult question that cannot be answered in a yes/no fashion. Instead, the uncertain knowledge of the various climate impact components asks for a probabilistic treatment of the outcome of any mitigation measure and the final result will be a probability of success, if all uncertainties are taken into account.

Well known trade-offs exist between contrail avoidance versus additional fuel consumption leading to accompanying additional emissions of CO_2 and all other non-CO_2 substances (Grewe et al., 2017a, b), and between technical means to lessen fuel consumption (using hotter flames in the combustor) at the cost of enhanced NO_x formation in the engine.

Recently a paper has appeared (Prather et al., 2025, hereafter PGP) which proposes a probabilistic treatment of aviation trade-offs and their corresponding risks (that is the risk, that a mitigation measure does not lead to a lower climate impact). In this method, a newly introduced metric "global warming potential per activity" (GWA) for each aviation component is used to determine whether a reduction of one component's GWA (e.g. contrails or nitrogen oxides) by N percent, balanced by increased GWA of carbon dioxide by 1 %, would give a benefit for climate. GWA is explained by PGP to be computed in the same way as the absolute global warming potential (a mass-specific quantity), but without taking the final step, that is, without dividing it by the amount of the emission. It is instead computed for the total emission amount occurring over a period of time, e.g. one year. Since all GWA values are associated with certain degrees of uncertainty, a risk arises and PGP propose a method to determine this risk.

While PGP are, to my knowledge, the first authors who propose such a method, their work leaves issues open for discussion. PGP do not show the derivation of their method and just present the result. Their statistical model for uncertainties is a subjective selection from a set of alternative possibilities and the effect of their particular choice on the resulting risk-curve is not discussed. The notion "trade-off" is only used in a vague general meaning, and concrete examples of potential mitigation measures are not mentioned. Finally, the question for which kind of decisions the risk analysis could be applied, remains unclear.

The present paper tries to fill these gaps and to add a necessary discussion. The paper starts with the mathematical derivation of the method proposed by PGP. Several of PGPs assumptions and their consequences are discussed, and the paper ends with a set of conclusions.

2 Mathematical derivation of the method of PGP

PGP introduce their method for a risk analysis with this statement: "From the individual GWA probability distributions, we built a probability distribution of the GWA(non-CO_2) to GWA(CO_2) ratio. The complementary cumulative distributions of this ratio become the trade-off risk curves shown in Fig. 3". Unfortunately, there is no reference and no derivation which could help the interested reader to understand why the ratio distribution of a pair of GWAs is the method needed to assess the risk involved in a decision. Related to this problem is the difficulty to understand the precise meaning of the x axis in PGPs Fig. 3, labelled "CO_2 to non-CO_2 trade-off ratio (% : %)" for which PGP give three slightly different verbal interpretations, but no precise mathematical expression. In the following, the derivation of an inequality is presented that expresses the condition that a change in the aviation system reduces its climate impact. This derivation clarifies the meaning of the x axis of Fig. 3 as well. Note that the application of GWA underlies similar critique as its close relative, viz. the absolute global warming potential. There are doubts whether such metrics are appropriate for decision-making, particularly in considering trade-offs between short-lived climate forcers (like contrails) and the long-lived CO_2 (e.g. Shine, 2009). The current paper will not engage in this difficult discussions. Instead it only treats the mathematics of PGPs method and its consequences. The following derivation is a general one for any kind of metric M that represents a kind of a time-integral over (effective) radiative forcing of an emission component C. The concrete application of this to GWA is just a special choice that clarifies the interpretation of PGPs Fig. 3.

2.1 The trade-off inequality

Radiation impacts due to changes of the atmospheric composition, expressed as radiative forcings or effective radiative forcings (ERFs), are the basis for all calculations of CO_2 equivalent emission metrics (incl. GWA) and climate effects of aviation emissions (examples can be found in Fuglestvedt et al., 2010). A recent compilation of (effective) radiative forcings for aviation has been presented by Lee et al. (2021), who provides best estimates up to the year 2018 and 90 % confidence intervals for all aviation climate impact components.

Not all metrics can be used for trade-off considerations. Appropriate metrics must be additive and must be a monotonically increasing function of the corresponding emission. Thus, a metric like the absolute global warming potential (AGWP) is not usable, since it is "per kg of emission", that is, a mass-specific quantity (in spite of its qualifier "absolute"). To be additive, a metric must be an extensive quantity. For instance, energies and temperature *differences* are additive, but temperature itself, being an intensive thermodynamic quantity, is not additive. PGP use GWA, which is quite similar to AGWP, but the final step in its calculation, the division by the mass of the emitted component is not taken, such that GWA is indeed an extensive quantity that increases monotonically with the emitted mass. This justification for the introduction of GWA is not explicitly mentioned in the paper by PGP.

The "activity" considered by PGP is the complete aviation in 2018. For this activity, the ERF values are at hand in the compilation by Lee et al. (2021). One can imagine (a thought experiment) that in that year an operational or technical measure would have been permanently in force that would have led to changed ERF values overall. Mathematically, we can formulate a general metric as the result of application of an operator Φ on an ERF value. Φ stands for a mathematical operation (e.g. an integral) that maps the ERF into a metric. This mapping varies between species, e.g. if the integral involves different time-scales (for examples, please consider the overview paper by Fuglestvedt et al., 2010). These differences are contained in the definition of Φ via a parameter (vector or scalar) Π. For instance, the time integral for the calculation of GWA needs one time-scale for contrails, two for nitrogen oxides, but a number of time-scales (typically three) for carbon dioxide. Such parameters (e.g. perturbation life-times and weighting factors as listed by Fuglestvedt et al., 2010, in their Table 2) are comprised in Π. Thus one can write generally:

$$M_C = \Phi(\mathrm{ERF}_C; \Pi_C), \tag{1}$$

where Φ is the operator (e.g. the integral that leads to AGWP or GWA), and the particular coefficients for component C are stored in the parameter (vector or scalar) Π_C.

If technical and/or operational measures had been in force in the considered year 2018, the ERF values would have changed and, in turn, the metric values as well, such that

$$M'_C = \Phi(\mathrm{ERF'}_C; \Pi_C). \tag{2}$$

If the operator Φ is linear, then

$$\begin{aligned} M'_C - M_C &= \Phi(\mathrm{ERF'}_C; \Pi_C) - \Phi(\mathrm{ERF}_C; \Pi_C) \\ &= \frac{\mathrm{d}\Phi(\mathrm{ERF}_C; \Pi_C)}{\mathrm{dERF}_C} (\mathrm{ERF}'_C - \mathrm{ERF}_C) \\ &=: \mathcal{D}\Phi(\mathrm{C})\, \Delta\mathrm{ERF}_C, \end{aligned} \tag{3}$$

where the symbol $\mathcal{D}\Phi$ has been introduced as a convenient abbreviation for the derivative. The postulate that the chosen metric must monotonically increase with the emissions implies that it also increases monotonically with ERF (for climate-warming agents). Thus, the derivative is positive. One can already note here that the ERF values per se do not appear in the balance, only their changes. Consequently, the final result does not depend on the ERF values. PGP's recommendation for an accurately as possible knowledge of ERFs is certainly desirable, but it does not follow as a consequence of the trade-off and risk analysis.

The total effect of two or more impacts is the sum of the metrics (this is the reason to postulate additivity), and the sum of the changes should be negative. With two opposing effects, say X and Y, this reads

$$(M'_X - M_X) + (M'_Y - M_Y) \leq 0 \tag{4}$$

and implies (see Fig. 1 for an illustration)

$$\mathcal{D}\Phi(X)\, \Delta\mathrm{ERF}_X + \mathcal{D}\Phi(Y)\, \Delta\mathrm{ERF}_Y \leq 0, \tag{5}$$

which is equivalent to

$$\frac{\mathcal{D}\Phi(X)}{\mathcal{D}\Phi(Y)} \leq -\frac{\Delta\mathrm{ERF}_Y}{\Delta\mathrm{ERF}_X}. \tag{6}$$

The expressions on both sides of this inequality are positive. Taking the inverse of both fractions and assuming that component Y is reduced while X increases, leads to

$$\frac{\mathcal{D}\Phi(Y)}{\mathcal{D}\Phi(X)} \geq \frac{1}{\frac{|\Delta\mathrm{ERF}_Y|}{\Delta\mathrm{ERF}_X}}. \tag{7}$$

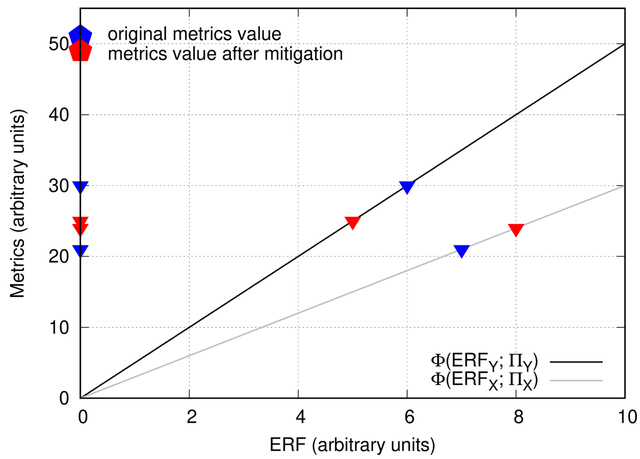

Figure 1. Metrics $M = \Phi(\mathrm{ERF}; \Pi)$ as function of ERF. The two functions Φ (black and grey, assuming linear dependence of Φ on ERF) have different slopes, indicating different sensitivity of the metrics to the ERF values. Two pairs of ERF values (blue and red triangles) represent current (blue) ERF values for the X and Y components and the analogue after a successful mitigation measure (red), which in the shown case is assumed to increase and decrease the two ERF values by the same amount. Since ERF_Y is reduced along a steeper slope while ERF_X is increased along the flatter one, the final outcome (sum of the corresponding metrics values values, blue and red pentangles) is beneficial for climate, since the original summed-up metrics (blue pentangle) has a higher value than that after mitigation (red pentangle). Note that the result (that is, the difference between the blue and red pentangles) is independent of the original ERF values; it depends only on the slopes of the Φ vs. ERF relation and the difference of the original and final ERF values.

In this equation, the lhs (the ratio of the derivatives) is the uncertain part which needs a probabilistic treatment, while the rhs (changes of the ERFs) depends on the concrete mitigation measure which we must assume (at least as a working hypothesis, to be discussed later) to be represented by a certain number. Let us thus assume that in a certain mitigation measure one unit of increase of ERF_X allows a reduction of ERF_Y by n units. Then the condition for a positive outcome is:

$$\frac{\mathcal{D}\Phi(Y)}{\mathcal{D}\Phi(X)} \geq \frac{1}{n}, \tag{8}$$

an expression that resembles the one arrived at by PGP, but with different interpretation.

The lhs of this trade-off equation is not the ratio of any metrics as in PGP's derivation. It is rather the ratio of a pair of sensitivities, namely the sensitivity of the chosen metric to the change of the basic (effective) radiative forcing at the current values of these quantities (see again Fig. 1). This form of the trade-off inequality might be called the "sensitivity form", because it involves the ratio of a pair of sensitivities instead of a pair of metrics. The trade-off ratio itself, that is, the *change* in the two ERF values due to a particular technical or operational modification of the system, is hidden in the simple $1:n$ ratio.

If the operators Φ_C involve uncertain coefficients Π_C, the derivatives are uncertain and can be described by PDFs. Analogously, the ratio of the derivatives is then uncertain and can be described by a PDF as well, and the CCDF of that ratio describes the probability that it exceeds $1:n$, that is, that the outcome is positive.

The original ERF values do not appear in the final result, only their respective changes due to the chosen mitigation measure, and the risk of the trade-off comes in via the uncertain parameters in the operators that translate ERF-values into climate metrics. In the light of this result, PGP's postulate that "clearly the most pressing need is to firmly establish the ERF calculations" appears as an exaggeration.

This general theoretical program will be applied to GWA in the next section. Another application is given in the Appendix.

2.2 Application to GWA

In this section we choose for $\Phi(\mathrm{ERF}_C;\Pi_C)$ the integral operator that leads from ERF to GWA. GWA is obtained like AGWP from the initial radiative forcing as an integral over a time horizon, but without the final step of division by the emitted mass of the substance in question. The definition of AGWP is (see, e.g., Fuglestvedt et al., 2003; Joos et al., 2013)

$$\mathrm{AGWP}_C(H) = \int_0^H A_C\, I_C(t)\,\mathrm{d}t = A_C \int_0^H I_C(t)\,\mathrm{d}t \qquad (9)$$

where A_C is the effective radiative forcing per kg increase in the component C in the atmosphere, that is, $\mathrm{ERF}_C = A_C \cdot m_C$, where m_C is the emitted mass of C due to the considered activity that leads from AGWP_C to GWA_C. That is, we use $\mathrm{GWA}_C = M_C = \Phi(\mathrm{ERF}_C;\Pi_C) = \mathrm{ERF}_C \int I_C(t;\Pi_C)\,\mathrm{d}t$. $I_C(t;\Pi_C)$ is the impulse response function of component C. $I_C(t)$ has a simple exponential form for, e.g., contrail cirrus, ozone and methane, that is, $\exp(-t/\alpha_C)$ (that is, the parameter $\Pi_C = \alpha_C$ is the atmospheric lifetime of the perturbation of C). For CO_2 the expression must include more than one atmospheric decay time-scale (usually three), that is, Π_{CO_2} is a parameter vector. Once the horizon H is fixed, the integral over $I_C(t;\Pi_C)$ has a certain value $K_C(H)$, that depends on the chosen horizon and which is specific to the component in question. GWA_C is thus the product $\mathrm{ERF}_C \cdot K_C(H)$. Thus, the sensitivity factor introduced above (Eq. 3) is simply $\mathcal{D}\Phi(C) = K_C(H)$. The postulate for a climate benefit then reads:

$$K_X(H)\Delta\mathrm{ERF}_X + K_Y(H)\Delta\mathrm{ERF}_Y \leq 0. \qquad (10)$$

Since $K_C(H) = \mathrm{GWA}_C/\mathrm{ERF}_C$ this can be rewritten as

$$\mathrm{GWA}_X \frac{\Delta\mathrm{ERF}_X}{\mathrm{ERF}_X} + \mathrm{GWA}_Y \frac{\Delta\mathrm{ERF}_Y}{\mathrm{ERF}_Y} \leq 0. \qquad (11)$$

Sorting the GWA and ERF terms on the two sides of the inequality, and assuming that component Y is reduced while X is increased, gives

$$\frac{\mathrm{GWA}_Y}{\mathrm{GWA}_X} \geq -\frac{\Delta\mathrm{ERF}_X/\mathrm{ERF}_X}{\Delta\mathrm{ERF}_Y/\mathrm{ERF}_Y} = \frac{\Delta\mathrm{ERF}_X/\mathrm{ERF}_X}{|\Delta\mathrm{ERF}_Y|/\mathrm{ERF}_Y} = 1 : \frac{|\Delta\mathrm{ERF}_Y|/\mathrm{ERF}_Y}{\Delta\mathrm{ERF}_X/\mathrm{ERF}_X}. \qquad (12)$$

The final version of the equation is again in the format suggested by PGP.

Now the meaning of the curve and the %:% unit in PGP's risk calculation becomes clear. It is not just "an N percentage reduction in the non-CO_2 impact" vs. a "1 % increase in CO_2 emissions", it is precisely the ratio of a relative reduction of a non-CO_2 (effective) radiative forcing (Y) to the relative increase of the corresponding CO_2 (effective) radiative forcing (X).

The problem with the latter equation is that uncertain quantities appear on both sides of the equation: On the lhs both GWA values, on the rhs the ERF values are uncertain. It is thus inadequate to write the lhs in the form $1:n$. The latter would imply that the relative ERF changes would rather exactly be known, but this is not the case if the reference state ERFs are uncertain. Thus, it is not allowed for a certain mitigation measure to pick a certain $1:n$ on the x axis of PGPs Fig. 3; it would rather be necessary to consider an interval or a worst case value for which the CCDF of the GWA ratio would need to be determined. As an illustration of this, let us assume that contrail avoidance would lead to an absolute reduction of contrail ERF that is ten times larger than the corresponding increase of the CO_2 ERF, that is, let $|\Delta\mathrm{ERF}_{\mathrm{CiC}}| = 10 \times \Delta\mathrm{ERF}_{CO_2}$. To mark a trade-off ratio in PGPs Fig. 3 it is necessary then to multiply this ratio of absolute changes with the ratio of the uncertain ERFs, for which it makes sense to assume a lognormal ratio consistent with PGPs assumptions. From this ratio distribution 1000 samples are drawn and used to estimate the percentiles of this distribution. These are then multiplied by $1:10$, that is, by the ratio of the absolute ERF changes. The result is the distribution of the unknown rhs in Eq. (12), presented as percentiles on the x axis (blue lines in Fig. 2). The rightmost blue line marks the 99th percentile of this distribution, which could be considered in a risk-adverse decision or following the precautionary principle. Note that the x value $1:10$ ($x = 0.1$) lies approximately at the 36th percentile, that is, most of the distribution of the ratio of the relative ERF changes lies to the right of $1:10$ where the risk is higher than at $1:10$. It means that although the ratio of absolute ERF changes may be $1:10$, the corresponding ratio of relative ERF changes may be much larger, implying a much higher risk than if the risk would be naively read-off at $1:10$ on the x axis. In order to avoid this undesired consequence, the absolute ΔERF change for contrails must exceed that of CO_2 by a much larger factor than 10. The 99th percentile of the ratio

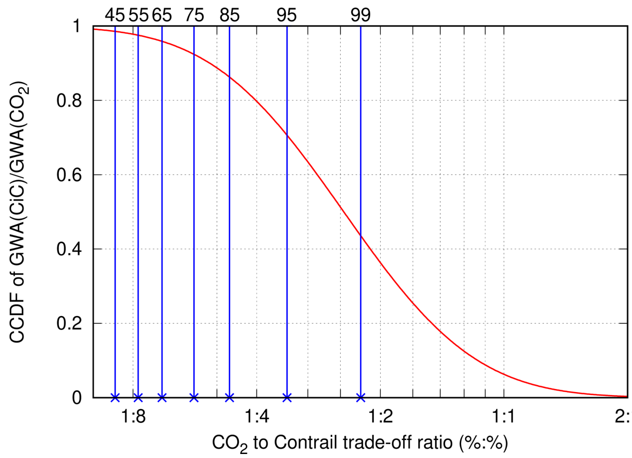

Figure 2. The trade-off risk curve (using the CCDF of the GWA ratio) illustrated for a case with an absolute trade-off ratio $|\Delta \mathrm{ERF}_{\mathrm{CiC}}| = 10 \times \Delta \mathrm{ERF}_{\mathrm{CO_2}}$, for which the distribution of the corresponding relative trade-off ratio that is needed for the x axis of PGPs Fig. 3 is given as percentiles (blue lines), from right to left as indicated on the upper axis. The value 1 : 10 itself corresponds approximately to the 36 % percentile and most of the distribution of the unknown ratio of the relative ERF changes lies to the right on the x axis where risks are larger. Thus, the absolute 1 : 10 trade-off ratio can correspond to a relative trade-off ratio that is larger than 1 : 10 under most circumstances and much larger under unfavourable ones, that is, when the unknown ERF ratio itself is large. This implies that the true risk can be much larger than the risk that one might read off at the absolute trade-off ΔERF ratio.

of relative ERF changes would be shifted to approximately 1 : 5 with a success probability of 0.9 if the ratio of absolute ERF changes was lowered to about 1 : 22, such that most of the distribution of the relative ERF changes lies outside the figure, where the risk curve is flat. This undesired property renders the method of PGP ill-defined and thus inadequate for its designed purpose.

The CCDF of the GWA ratio in this figure (red curve) has been computed analytically, which is possible once the single GWA distributions are taken as log-normals. The ratio distribution is then log-normal as well and its CCDF, $\overline{F_X}(x)$ is:

$$\overline{F_X}(x) = \frac{1}{2} - \frac{1}{2}\,\mathrm{erf}\left[\frac{\ln(x/\mu^*)}{\sqrt{2}\,\ln\sigma^*}\right], \tag{13}$$

which involves an error function erf(·) that is defined by geometric mean μ^*_C and standard deviation σ^*_C, determined from the involved GWA_C uncertainty distributions. For the case of contrails (CiC) and a time horizon of 100 years, $\mu^* = \mu^*_{\mathrm{CiC}}/\mu^*_{\mathrm{CO_2}}$ and $\sigma^* = \sigma^*_{\mathrm{CiC}}\,\sigma^*_{\mathrm{CO_2}}$ with the geometric means and standard deviations from PGP's table: ($\mu^*_{\mathrm{CiC}} = 33$, $\mu^*_{\mathrm{CO_2}} = 81$, $\sigma^*_{\mathrm{CiC}} = 1.55$, $\sigma^*_{\mathrm{CO_2}} = 1.16$). With the analytical expression, the CCDF of PGP can be obtained (apart from minor differences due to rounding), as shown in Fig. 2.

The correct form of the risk analysis, that is, the sensitivity form, has the uncertain components on one side of the equation and on the other side there is the expression that characterizes the change in the system. In the present case, this risk-equation is

$$\frac{K_Y(H)}{K_X(H)} \geq \frac{1}{|\Delta \mathrm{ERF}_Y|/\Delta \mathrm{ERF}_X} =: 1:n, \tag{14}$$

for which the $1:n$ representation of the x axis is justified if and only if the individual changes of ERF can be determined with a better precision than the uncertainty of the sensitivity factors. This might be possible, see the discussion in Sect. 3.1, but if not, then there is no possibility at all to conduct a climatological risk assessment that is based on the postulate that the eventual sum of the chosen metric should get reduced. In this case, completely new strategies are needed. Recall that the quantities $K_C(H)$ are the integrals of the impulse response functions over the chosen time horizon. Uncertain parameters are thus the parameters of the response functions. These are lifetimes in the exponential expressions and, in case of CO_2, the weighting factors of the different lifetimes (see e.g. Fuglestvedt et al., 2010, their Table A1).

3 Discussion

3.1 On the uncertainty of ΔERF

It has been shown that the method works only appropriately if the central trade-off inequality (Eq. 7) has the uncertain quantities collected on one side, and relatively certain ones on the other. For the derivation it was necessary to assume that Δ ERF should be known to a degree much better than the original ERF values. But the question arises whether such an assumption is justified, considering that Δ ERF is the difference of ERF′ and ERF, which both are uncertain. The answer is that indeed this assumption can be justified. ERF′ and ERF must be calculated using a global model. Certainly such a model has, as every model, flaws and inadequacies in its representation of relevant physical processes. This can introduce a systematic error in the calculation of ERF. However, the systematic error is produced both in the calculation of ERF and in that of ERF′ in a very similar way, such that it cancels once the difference is taken. This fact is always exploited when a pair of simulations is performed, one with and one without aviation, to isolate the aviation effect. The uncertainty bars shown in the diagram of Lee et al. (2021) reflects the differences between several global models to calculate ERFs. This uncertainty does not apply since ERF′ and ERF need to be computed with one and the same model and ideally the same weather pattern (over the course of a year or longer) in both runs. This can in principle be assured using nudging. If the weather patterns could not be guaranteed to be equal in both model runs, then ERF′ and ERF would not be comparable (note that there is a strong interannual variation due to the weather, see Gettelman et al., 2021; Wilhelm et al., 2021) and the resulting difference would be meaningless and not usable for a risk assessment. What results when ΔERF is determined with various models, would need to be tested. It is not clear whether the error cancellation works in the same way for different models.

Anyway, should for any reason Δ ERF be as uncertain as ERF and in particular less certain than the involved pair of sensitivities, then there is no way to conduct a climatological risk assessment that is based on the postulate $M' - M \leq 0$. In this case the method is not applicable, neither in the sensitivity form nor in PGPs form and for no kind of metrics.

3.2 Choice of the statistical model for the uncertainty distribution

GWAs are derived from values of effective radiative forcings (ERFs) via integration over a time horizon, a linear operation. Lee et al. (2021) provide estimates of ERFs of aviation emissions. These are uncertain and thus presented as best estimates and *symmetric* error bars which represent 90 % confidence intervals (1.645σ). These error bars comprise various sources of uncertainty, but not all. Lee et al. (2021) write in their Appendix E that the number of available studies is too small for a robust uncertainty estimate of the contrail forcing. They considered in their study two sources of uncertainty, which both originate from the individual method how radiative effects and contrail and cirrus microphysics are treated in the respective model. Other uncertainties, in particular that due to a wide annual variability from changing weather (Gettelman et al., 2021; Quaas et al., 2021; Wilhelm et al., 2021) are not regarded. It is evident, that the actual global contrail ERF uncertainty is larger than what is estimated by Lee et al. (2021). While the CO_2 uncertainty distribution is relatively narrow, in particular that of contrails is quite wide. If the uncertainty distribution would be modelled as a normal PDF, a small probability for negative ERF of contrails would result. In contrast the choice of a log-normal model to describe the uncertainty distribution does not allow values of both signs to appear; the values are strictly positive or strictly negative. For contrails with a log-normal uncertainty PDF, the possible ERF values are strictly positive. This is presumably the idea which PGP had in mind when they chose log-normal (that is asymmetric) uncertainty PDFs, although it is not stated in that paper.

The ERF distributions (probability density functions, PDFs) for CO_2 and contrail cirrus (CiC), interpreted both as normal and log-normal distributions are shown in Fig. 3.

The risk function for an underlying normal distribution of the GWA uncertainties has been computed using the geometric means and standard deviations from PGPs table, translated into normal distributions, keeping the 68 % ($\pm\sigma$) confidence levels. In this case, the ratio distribution is not simply given as an analytic expression and must be obtained using a Monte Carlo experiment. The result is presented in Fig. 4.

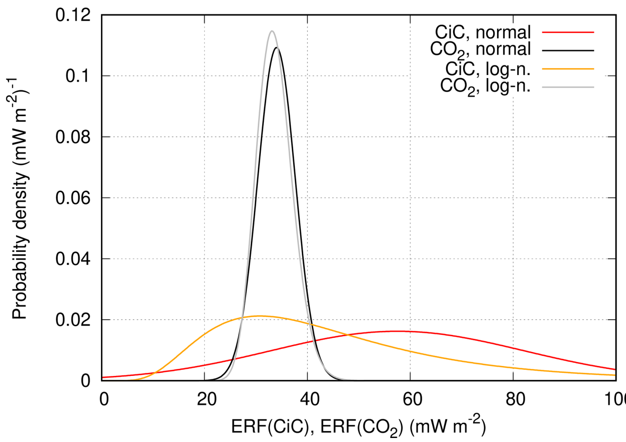

Figure 3. Probability density functions for the unknown true values of ERF for CO_2 and contrail induced cirrus (CiC) using best estimates and 90 % confidence intervals from Lee et al. (2021). Two model distributions for the underlying uncertainty are used, the normal distribution (red and black curves), which are symmetric as the error bars in Lee et al. (2021) suggest, and the log-normal distribution as used by PGP (orange and gray curves).

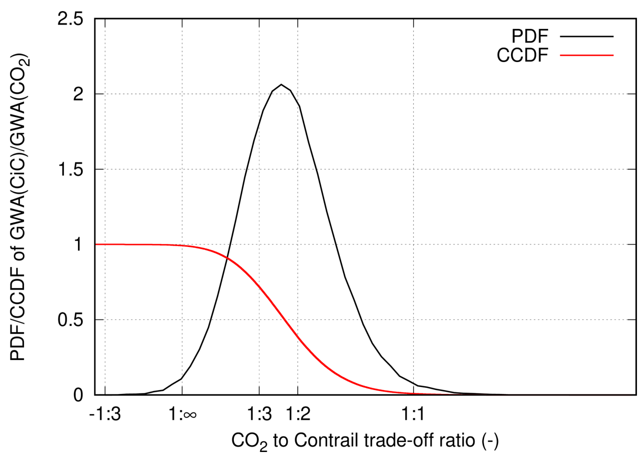

Figure 4. Probability density and CCDF of the GWA ratio for contrails and CO_2 for the case of a normal distribution of the uncertainties. The chosen time horizon is 100 years.

The black curve shows the PDF of the GWA ratio, which extends (with small probability) to negative numbers. Consequently, the CCDF extends into the negative range as well and crosses the trade-off ratio $1:\infty$. This signifies that no trade-off occurs when contrails were cooling in the global and multi-annual average. However, as the red curve shows, the probability that the GWA ratio is positive (that is, that contrails warm the climate) is practically unity. This example demonstrates clearly that the risk curve is different from the original one (red curve in Fig. 2).

In fact, there is no particular reason to assume a normal uncertainty distribution at all; one could select as well a triangular or a uniform distribution, each time with a different re-

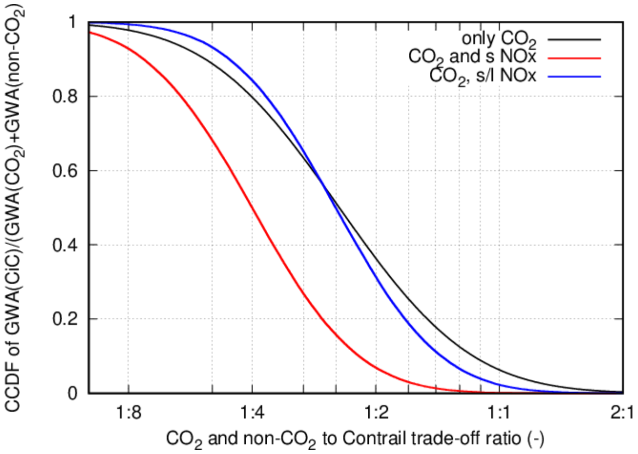

Figure 5. CCDF of the GWA ratio for contrails and $CO_2 + NO_x$ for the case of a log-normal distribution of the uncertainties. The red curve represents the addition of the short NO_x (i.e. O_3) effect alone, while the blue curve involves both short- and long NO_x effects in a way that mimics their correlation, that is, their partial cancellation. The chosen time horizon is 100 years.

sulting risk curve $\overline{F}(x)$. Ideally, the choice should be guided by physical arguments (similarly to the choice of a prior distribution in Bayes-statistics, see Epstein, 1985). However, as there are few global models that can provide GWAs or other global metrics for aviation emissions, the statistical basis for a well-conceived choice is thin. As long as the choice of the distribution model for the GWA uncertainty distribution is a mere subjective choice (perhaps for the reason of more convenient mathematics), the resulting risk function $\overline{F}(x)$ cannot be regarded as an objective measure of trade-off risk.

3.3 Taking into account all gaseous emissions for contrail mitigation

Rerouting for the purpose of contrail avoidance implies deviations from the cost-optimal path, which in most cases requires the burning of additional fuel. This leads to increased gaseous emissions, not only of CO_2 but of all other combustion products as well, in particular NO_x. The proper trade-off consideration of rerouting for contrail avoidance needs thus to account for all additional emissions, not only CO_2. Following PGP by computing the CCDF of the ratio of GWA(CiC) to GWA(other emissions) for that purpose implies the need to compute the PDF of the sum of the GWAs of CO_2 and the other gaseous emissions first, before the ratio is taken. It follows that first one has to compute the probability density function of the sum of the GWAs of CO_2 plus the other gaseous emissions, for instance via a Monte Carlo method. The desired CCDF of the GWA ratio is then achieved from a Monte Carlo calculation as well. For the calculation, the mean values and standard deviations from the table of PGP are used. The result for taking short- (ozone) and long- (mainly methane) term NO_x effects into account is shown in Fig. 5. The black curve is just the copy from Fig. 2; it takes only CO_2 into account. The red curve shows the risk curve, if additionally the ozone effect from NO_x is considered. The addition of ozone into the trade-off ratio leads to a quite different risk curve than the original one. The curve becomes much flatter which means that the probability of success for a certain trade-off ratio gets considerably lower. That would imply in turn that much more contrail effect would need to be reduced for one unit of a combined CO_2 and ozone effect to get a high probability of success. The blue curve represents the case where both, the short and long-term NO_x effects are accounted for. A problem for the proper treatment is the correlation between these two effects, which implies that they cannot be added as independent stochastic quantities. A simple solution for this case is to treat them as one effect with a GWA distribution, where the mean and variance are, respectively, the sum of the two means and the two variances. All these numbers have been computed using the entries in PGP's table. The blue curve is close to the original black one because of the partial cancellation of the short- and long-term NO_x effects. The treatment of the correlation is certainly too simple for real applications, but it is sufficient for the present goal, that is, to demonstrate that when determining the risk of contrail avoidance it is not sufficient to just consider the trade-off with CO_2 alone.

4 Conclusions

The present paper supplements a recent paper by Prather et al. (2025) (PGP), who propose a statistical method for risk assessments that are required for mitigation decisions in aviation that involve trade-offs. As PGP propose their method without giving mathematical details, the method itself and its implications are difficult to understand in the desired depth. In order to fill this gap, the full mathematical derivation of this method is given here. In particular, the derivation explains to what extent the ratio distribution of a pair of additive metrics (in this case GWAs, global warming potential per activity), more precisely its complementary cumulative distribution function, is thought to be the tool needed for a risk assessment. The derivation leads furthermore to a precise definition of the "trade-off ratio" on the x axes of PGP's central methodical Fig. 3.

The final result is an inequality that expresses the postulate that a change in a system must lead to a new state where the sum of additive metrics is smaller than in the old state of the unmodified system. Surprisingly, this condition does not lead to an expression involving metrics or (effective) radiative forcings any more; it does only contain the changes of the ERFs (due to the taken measure) on one side of the inequality and a ratio of sensitivities (that is the change of the metric divided by the change of the underlying ERF, a derivative) on the other. If the presence of a ratio of metrics (e.g. GWA) is enforced on one side of the inequality, the ratio of ERFs appears automatically on the other side. Then both sides of the inequality contain uncertain quantities and the method does no longer work. Thus, the method of PGP does not allow the desired risk analysis.

PGPs method might work in the "sensitivity" form, that is, in the form that contains the uncertain sensitivities on one side and the ERF changes on the other side of the inequality. A method directly involving climate sensitivity factors (Bickel et al., 2025) and aiming at a reduction of the equilibrium temperature change due to aviation effects is given in the Appendix. Whether the method works in sensitivity form depends certainly on the precision with which the ERF changes can be determined. This precision should be considerably better than the width of the distribution of the ratio of sensitivities. In principle, this could be possible, since, if ERF without and with the mitigation measures in place is computed with the same global model and for the same weather pattern over the course of a year or longer (which can be assured by nudging), systematic errors from the model runs cancel when the difference $\mathrm{ERF}' - \mathrm{ERF}$ is taken. Whether the error cancellation works similar in various models, such that ERF changes would be sufficiently similar, remains to be tested. Unfortunately, such model calculations need quite some costly run-time of supercomputers, which renders the method inappropriate as a tool for decision making in daily applications. Rather it may be used to assess a past decision or mitigation measure in hindcast.

Appendix A: Numbers used in the calculations

For the calculation of the curves in Fig. 4 the following quantities have been used:

$$\mu_{\mathrm{CiC}} = 36.2, \sigma_{\mathrm{CiC}} = 14.9,$$

$$\mu_{\mathrm{CO_2}} = 81.9, \sigma_{\mathrm{CO_2}} = 12.1.$$

For the calculation of the risk-curves in Fig. 5 the following quantities have been used:

$$\mu^*_{\mathrm{CiC}} = 33., \sigma^*_{\mathrm{CiC}} = 1.55,$$

$$\mu^*_{\mathrm{sNO}_x} = 49., \sigma^*_{\mathrm{sNO}_x} = 1.45,$$

$$\mu^*_{\mathrm{lNO}_x} = -30.17, \sigma^*_{\mathrm{lNO}_x} = 1.13,$$

$$\mu^*_{\mathrm{CO_2}} = 81., \sigma^*_{\mathrm{CO_2}} = 1.16.$$

The starred quantities are geometric means and standard deviations. The correlation between the NO_x effects has been modelled by using a single GWA distribution with

$$\mu^*_{\mathrm{NO}_x} = \mu^*_{\mathrm{sNO}_x}\,\mu^*_{\mathrm{lNO}_x} = 1.62, \quad \sigma^2_{\mathrm{NO}_x} = \sigma^2_{\mathrm{sNO}_x} + \sigma^2_{\mathrm{lNO}_x},$$
thus $\sigma^*_{\mathrm{NO}_x} = \exp(\sigma_{\mathrm{NO}_x}) = 1.48.$

Appendix B: Alternative example involving the equilibrium temperature change

Let us consider the trade-off between contrail avoidance and the generally required additional fuel for the necessary deviations from the fuel-optimal routes, which leads to additional emission of, for instance, $\mathrm{CO_2}$. Then let

$$\Delta\mathrm{ERF}_X = \mathrm{ERF}'_{\mathrm{CO_2}} - \mathrm{ERF}_{\mathrm{CO_2}} \text{ for } \mathrm{CO_2} \quad \text{(B1)}$$

$$\Delta\mathrm{ERF}_Y = \mathrm{ERF}'_{\mathrm{CiC}} - \mathrm{ERF}_{\mathrm{CiC}} \text{ for contrail cirrus.} \quad \text{(B2)}$$

In this Appendix the trade-off risk calculation is performed in terms of the equilibrium near-surface temperature change, $\Delta T_{\mathrm{eq}}^{X,Y}$, caused by the corresponding effective radiative forcings, that is the operator $\Phi_{X,Y}$ is set simply to the corresponding climate sensitivity factors, such that M_X and M_Y become $\Delta T_{\mathrm{eq}}^{X,Y}$. One can then use climate sensitivity factors from Bickel et al. (2025) to convert the ERF values from Lee et al. (2021) into (surface) temperature changes (in equilibrium), that is:

$$\Delta T_{\mathrm{eq}}^{\mathrm{CO_2}} = \lambda_{\mathrm{ERF}}^{\mathrm{CO_2}} \cdot \mathrm{ERF}_{\mathrm{CO_2}}, \ \Delta T_{\mathrm{eq}}^{\mathrm{CiC}} = \lambda_{\mathrm{ERF}}^{\mathrm{CiC}} \cdot \mathrm{ERF}_{\mathrm{CiC}}. \quad \text{(B3)}$$

The contrail avoidance measures would change the ERF values and thus result in different equilibrium temperature changes, $(\Delta T_{\mathrm{eq}}^{X,Y})'$. Let us write the corresponding change of the total equilibrium temperature increase as $(\Delta T_{\mathrm{eq}}^{X,Y})' - (\Delta T_{\mathrm{eq}}^{X,Y}) =: \Delta\Delta T_{\mathrm{eq}}^{X,Y}$. Then this difference of differences due to both contrail avoidance and the accompanying increase of $\mathrm{CO_2}$ emission is the sum of the individual contributions, that is

$$\begin{aligned}\Delta\Delta T_{\mathrm{eq}} &= \Delta\Delta T_{\mathrm{eq}}^{\mathrm{CO_2}} + \Delta\Delta T_{\mathrm{eq}}^{\mathrm{CiC}} && \text{(B4)}\\ &= \lambda_{\mathrm{ERF}}^{\mathrm{CO_2}}(\mathrm{ERF}'_{\mathrm{CO_2}} - \mathrm{ERF}_{\mathrm{CO_2}})\\ &+ \lambda_{\mathrm{ERF}}^{\mathrm{CiC}}(\mathrm{ERF}'_{\mathrm{CiC}} - \mathrm{ERF}_{\mathrm{CiC}}). && \text{(B5)}\end{aligned}$$

Whether the change $\Delta\Delta T_{\mathrm{eq}}$ is positive or negative (that is, whether the assumed measures have increased or decreased the overall temperature change) is simple to calculate and no statistics is necessary, as long as one knows what one does, that is, if one knows the changes $\Delta\mathrm{ERF}$ for both components, contrail cirrus and $\mathrm{CO_2}$. Before it is possible to estimate how $\Delta\mathrm{ERF}$ will change as a result of the mitigation, this mitigation measure should be avoided. Once $\Delta\mathrm{ERF}$ can be estimated, the sign of $\Delta\Delta T_{\mathrm{eq}}$ can be computed without difficulty as soon as the conversion factors are known. Indeed, the result is good for climate (that is $\Delta\Delta T_{\mathrm{eq}} \leq 0$) as soon as $-\Delta\,\mathrm{ERF}_{\mathrm{CiC}} \geq (\lambda_{\mathrm{ERF}}^{\mathrm{CO_2}}/\lambda_{\mathrm{ERF}}^{\mathrm{CiC}})\Delta\,\mathrm{ERF}_{\mathrm{CO_2}} = 2.63 \times \Delta\,\mathrm{ERF}_{\mathrm{CO_2}}$, using the climate sensitivity factors from Bickel et al. (2025). So far, no risk at all appears in the calculation.

However, the climate sensitivity factors from Bickel et al. (2025) are uncertain. They have been determined from one single model study, and simulations with different global models would certainly yield different sets of factors. The

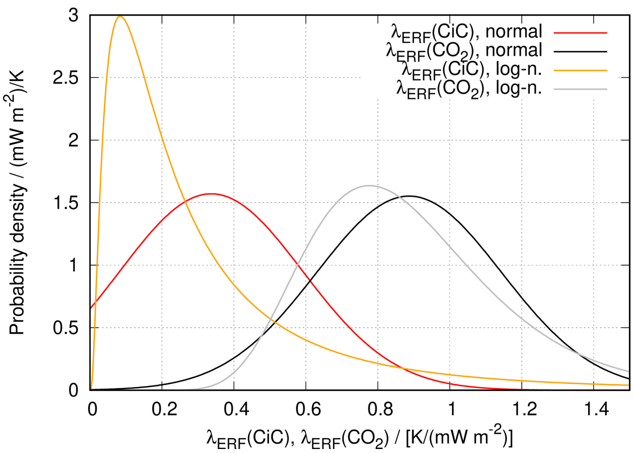

Figure B1. Probability density functions for the unknown true values of λ_{ERF} for CO_2 and contrail induced cirrus (CiC) using best estimates and 90 % confidence intervals from Bickel et al. (2025). Two model distributions for the underlying uncertainty are used, the normal distribution (red and black curves), which are symmetric as the error bars in Bickel et al. (2025) suggest, and the log-normal distribution (orange and gray) used to avoid the possibility of negative values.

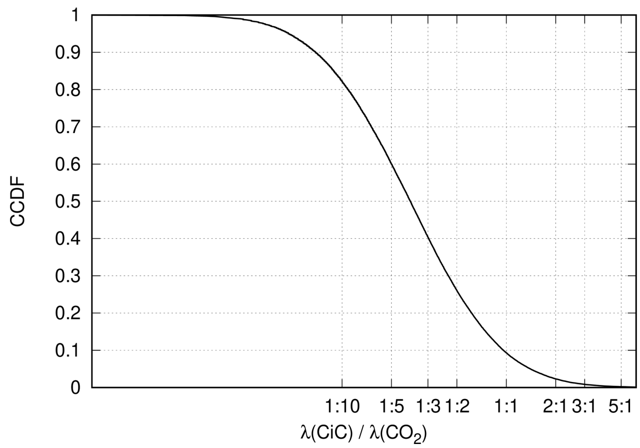

Figure B2. Risk curve in the form of PGP's one.

associated systematic uncertainty cannot be quantified so far. Bickel et al. (2025) give uncertainty ranges for the climate sensitivity factors (in $\mathrm{K\,(mW\,m^{-2})^{-1}}$):

$$\lambda_{\mathrm{ERF}}^{\mathrm{CO_2}} = 0.887 \pm 0.257;\ \lambda_{\mathrm{ERF}}^{\mathrm{CiC}} = 0.337 \pm 0.254. \tag{B6}$$

The quoted uncertainties are one standard deviation and originate from the year-to-year variability in the simulation (which resembles the natural year-to-year variability). The ±-sign with a single value for the standard deviation suggests a symmetric uncertainty distribution, but in the contrail case the zero is only 1.33σ away from the best estimate which involves non-negligible potential for negative values. Thus, in order to avoid negative sensitivity values, it is preferable (like PGP) to resort to a log-normal model for the uncertainty distribution of the climate sensitivity factors, which allows an analytical solution in analogy to Eq. (13). The geometric standard deviations and means are then (no units):

$$\sigma_\lambda^*(\mathrm{CO_2}) = 1.35;\ \mu_\lambda^*(\mathrm{CO_2}) = 0.85 \tag{B7}$$

$$\sigma_\lambda^*(\mathrm{CiC}) = 2.67;\ \mu_\lambda^*(\mathrm{CiC}) = 0.22 \tag{B8}$$

The resulting uncertainty distributions are presented in Fig. B1 This statistical model does now allow a risk analysis.

As stated above, if one knew the climate sensitivity factors exactly, there is no risk at all and the climate impact of contrail avoidance would be positive (or rather, would have been positive if in 2018 enough contrails had been avoided) in the case where for one unit of increase of the ERF of CO_2 at least $(\lambda_{\mathrm{ERF}}^{\mathrm{CO_2}}/\lambda_{\mathrm{ERF}}^{\mathrm{CiC}}) = 2.63$ units of ERF of contrail cirrus had been saved. If, however, the true climate sensitivity factors differ from the best estimates of Bickel et al. (2025), then also the factor differs from 2.63. The climate effect of contrail avoidance is positive as soon as the reduction of the contrail ERF exceeds $(\lambda_{\mathrm{ERF}}^{\mathrm{CO_2}}/\lambda_{\mathrm{ERF}}^{\mathrm{CiC}})$ times the increase of the ERF of CO_2.

With the distribution parameters of the log-normal model one can compute the CCDF of the ratio $\lambda_{\mathrm{ERF}}^{\mathrm{CiC}}/\lambda_{\mathrm{ERF}}^{\mathrm{CO_2}}$, which is plotted in Fig. B2, similarly to the plots of PGP. The interpretation is as indicated in Sect. 2.2. Basically, the CCDF curve gives the probability that the ratio of the climate sensitivities exceeds the value given on the x axis. For instance, the probability that this ratio is larger than 1 : 10 is about 80 %, and the probability that the ratio exceeds 1 : 3 is about 40 %. (The probability that the climate sensitivity factor of contrails is equal to or even exceeds that of CO_2 is about ten percent). This implies that an ERF(CiC) reduction that is three times larger than the corresponding ERF(CO_2) increase is positive for climate, that is, would lead to a reduced equilibrium temperature increase, as soon as $\lambda_{\mathrm{ERF}}^{\mathrm{CiC}}/\lambda_{\mathrm{ERF}}^{\mathrm{CO_2}}$ exceeds 1 : 3. In this case there is a 40 % chance that the final outcome is good for climate, while it would give an 80 % chance, if the ERF(CiC) reduction is ten times larger than the ERF(CO_2) increase. Of course these values underestimate the actual risk, since the uncertainty of the climate sensitivity factors is underrepresented if only the statistical variability of the climate but no systematic uncertainty is taken into account.

Instead of using ERF to derive the equilibrium surface temperature change one can alternatively use the (stratosphere) adjusted radiative forcing (RF) together with the corresponding climate sensitivity factors that refer to RF, according to the relation $\Delta T_{\mathrm{eq}}^{\mathrm{C}} = \lambda_{\mathrm{RF}}^{C}\mathrm{RF}^{C}$ for any component C. Bickel et al. (2025) provide these quantities for CO_2 and contrail cirrus with mean values and standard deviations like for $\lambda_{\mathrm{ERF}}^{\mathrm{C}}$. RF can be determined for single flights which is not possible for ERF. Yet each flight leads to its individual chain of feedbacks, which are not considered when RF is used, such that on a single flight basis each GWA (per flight) has its own best value and its own uncertainty distribution, which furthermore must be broader than that of many flights since statistical variations cannot cancel for a single flight. This renders the method impractical for mitigation decisions applied to single flights even if RF would be used as a metric.

Code and data availability. This paper includes only analytical calculations. Software code was not necessary. The data used are only a couple of parameters (means and standard deviations) that all are given in the paper.

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