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Exchange rates, trade-offs and risks in mitigation options for aviation

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Abstract. A recently proposed method to mathematically treat trade-offs and associated risks in aviation mitigation options (Prather et al., 2025) leaves, to this author's opinion, many issues open for discussion. The method is critically reviewed and the equations are derived and justified. Issues that remained vague in the recent paper are clarified. Unfortunately, close inspection proves this method to be inadequate for its purpose. An alternative formulation is proposed with transparent and understandable derivations. The unfounded assumptions basic to the original method are discussed and their effects on the final result are shown. It turns out that with the current data basis the proposed risk-analysis method for mitigation in aviation suffer from a certain degree of arbitrariness. Alternative approaches that exploit ensemble weather forecasts seem more promising.

1 Introduction

In order to lessen aviation's climate impacts, a lot of strategies have been suggested and discussed (e.g. Sausen et al., 1994; Williams et al., 2002, 2003; Mannstein et al., 2005; Ponater et al.; 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 since the climate impacts 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., 2017b, a), 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, herafter 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 percent, would give a benefit for climate. 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 many issues open for discussion. The equations used by PGP are presented in an ad-hoc fashion, without derivation. Their statistical model for uncertainties is not convincingly justified 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 a critical review of the method proposed by PGP and then goes on with an alternative proposal. Several of PGPs assumptions and their consequences are discussed, and the paper ends with a set of conclusions.

2 Critical review of the method of PGP

2.1 Exchange rate vs. trade-off ratio

PGP begin with the statement "For climate trade-offs across GHGs [Greenhouse Gases], the standard metric is the global warming potential (GWP), which measures the average warming from 1 kg of emissions of any GHG relative to that from 1 kg of emissions of CO_2." To me, the immediate question arises whether it is appropriate to label the GWP as a trade-off measure or whether it is rather a kind of an exchange rate (or perhaps equivalence ratio). These notions may be related, but there are important differences. Exchange rates are basic quantities and do not depend on any measures that may involve a trade-off. Trade-off ratios may be determined via exchange rates, but not necessarily so. A few examples may suit to illustrate the difference.

Example 1: It is well known that ruminants such as cattle emit methane (CH_4). Methane has a GWP of about 28 on a time horizon of 100 years (Forster et al., 2021). Assuming a cow is slaughtered, the emission of methane is stopped, without any effect on CO_2. That is, there is an exchange rate (GWP), but it is not accompanied in this case with any trade-off.

Example 2: Although there is no (direct) physical connection between the cosmic ray exposition of an air crew and the fuel consumption of their aircraft, flying lower to reduce the cosmic ray dose rises fuel consumption and thus inevitably emissions. That is, there is a trade-off. One aspect of flying gets better, but causes another one to worsen. One cannot have both advantages

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at the same time. However, as the physical connection is merely indirect, there is no exchange rate, and if somebody would determine one for a special situation, it would clearly depend on the situation, that is, it cannot be generalised.

Example 3: Now assume a technical process that causes emissions of both CH_4 and CO_2. Assume that the turn of a screw leads to a reduction of the CH_4 emission at the expense of an increase of the emission of CO_2. This is a trade-off situation that can be analysed mathematically using the GWP. To turn the screw implies a benefit for climate only if $\mathrm{AGWP}_{\mathrm{CH_4}}\,\Delta\,\mathrm{CH_4} + \mathrm{AGWP}_{\mathrm{CO_2}}\,\Delta\,\mathrm{CO_2} \leq 0$, where $\mathrm{AGWP}_{\mathrm{C}}$ stands for the absolute GWP of species C. The condition is equivalent to

$$\mathrm{GWP}_{\mathrm{CH_4}} \geq \frac{1}{\frac{|\Delta\,\mathrm{CH_4}|}{\Delta\,\mathrm{CO_2}}} =: 1:n, \tag{1}$$

with

$$1:n = \frac{\Delta\,\mathrm{CO_2}}{|\Delta\,\mathrm{CH_4}|}, \tag{2}$$

expressing that one mass unit of CO_2 is expended for a saving of n mass units of CH_4. This simple result has been formulated in a way that resembles that of PGP, but there are certain differences. First it is necessary to note that in this equation $\mathrm{GWP}_{\mathrm{CH_4}}$ is uncertain and requires a probabilistic treatment while the right-hand side (rhs) ratio is determined by the technical change; it is a certain number and the risk analysis has to consider the question with which probability $\mathrm{GWP}_{\mathrm{CH_4}}$ equals or exceeds the given number $1:n$. In the treatment of PGP both sides of the equation contain uncertain quantities which renders the application of their risk-analysis method impossible. This will be shown in Sect. 3.3.

When GWP is used for a decision, the $\Delta\mathrm{C}$ (for any component C) quantities refer to singular emissions or more generally to changes of emission rates in a concrete situation, e.g. the turn of the screw. A trade-off arises only if there is a concrete change in a system with interdependent effects that go into opposite directions. Here, the GWP (which is the ratio of the AGWPs of methane and carbon dioxide) serves just as a critical (but quantitatively uncertain) value for the decision whether the screw should be turned or not. Without such a change, there is no trade-off, but the GWP keeps its sense as an exchange rate. PGP use a variant of GWP, or rather a variant of AGWP, namely the GWA, the global warming potential for a certain activity, which is the AGWP multiplied by the emission related to that activity. In this case, the rhs of eq. 1 gets a different meaning, which will become clear later.

2.2 Trade-off risk

A decision like that outlined above would be clear if the exchange rate between the two, say, effects were known exactly; in the example above, if the statement "$\mathrm{GWP}_{\mathrm{CH_4}} = 28$" were true and firm. However, this statement only describes a best guess and the true value of $\mathrm{GWP}_{\mathrm{CH_4}}$ is not known exactly, which makes decisions that are based on it uncertain. To formulate a decision requires a risk calculation and that proceeds along the lines shown by PGP. PGP calculate GWA for aviation emissions and effects in the complete year 2018. More precisely, since the true values are unknown, they assume probability density functions (PDFs) for the GWAs of CO_2, contrails (CiC, contrail induced cirrus), and chemical species that are affected by emissions of nitrogen oxides, NO_x. PGP assume that these PDFs are log-normal distributions. I will discuss this choice later (section 4.2). GWA, like AGWP and GWP, additionally depends on the choice of a time horizon, but as this is not relevant for the current

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discussion, I will choose arbitrarily a time horizon of 100 years in this paper for concrete examples. In terms of $\mathrm{GWA_C}$ (the GWA for an aviation-induced climate impact by emission of a species C or by contrails) a beneficial effect for climate following a change involving trade-off requires, in analogy to Eq. 1,

$$\frac{\mathrm{GWA_C}}{\mathrm{GWA_{CO_2}}} \geq \frac{1}{\frac{|\Delta\,\mathrm{C}|}{\Delta\,\mathrm{CO_2}}}. \tag{3}$$

As stated above, in this form, the $\Delta\mathrm{C}$ quantities are not interpretable as changed emission amounts or rates, because these are already contained in the definition of $\mathrm{GWA_C}$. The exact meaning will be clarified below. Note that the $1:n$ has not been added to the rhs of eq. 3, since this would signify that the rhs was a certain number, which it is not in this particular case. This will be demonstrated below. For the moment we simply assume that the rhs has a certain value and that only the GWAs were uncertain. As the true values of the GWAs are unknown, the inequality in this form is only applicable if particular choices for the GWA values are taken. Acknowledging the ignorance of the true values of GWA requires consideration of the probability distribution of the ratio $\mathrm{GWA_C}/\mathrm{GWA_{CO_2}}$, and its complementary cumulative distribution function (CCDF), $\overline{F_\mathrm{C}}(x)$, which is the probability that the ratio $\mathrm{GWA_C}/\mathrm{GWA_{CO_2}}$ is equal to or exceeds a given value x. The probability of a successful mitigation decision increases with the ratio $\mathrm{GWA_C}/\mathrm{GWA_{CO_2}}$, as eq. 3 shows. Or, in different words, if the GWA ratio is large it is easier to achieve a successful mitigation with a certain effort (ΔC), or with a large GWA ratio the minimum required effort for a successful mitigation can be small.

Once log-normal distributions for the GWAs are assumed, the distribution of their ratio is log-normal as well and the CCDF can be computed analytically, involving an error function $\mathrm{erf}(c)$ that is defined by geometric mean μ^*_C and standard deviation σ^*_C, determined from the involved $\mathrm{GWA_C}$ uncertainty distributions. This is demonstrated for the case of contrails (CiC) and a time horizon of 100 years:

$$\overline{F_\mathrm{X}}(x) = \frac{1}{2} - \frac{1}{2}\,\mathrm{erf}\left[\frac{\ln(x/\mu^*)}{\sqrt{2}\,\ln\sigma^*}\right], \tag{4}$$

where $\mu^* = \mu^*_\mathrm{CiC}/\mu^*_\mathrm{CO_2}$ and $\sigma^* = \sigma^*_\mathrm{CiC}\,\sigma^*_\mathrm{CO_2}$. Using the geometric means and standard deviations from PGP's table ($\mu^*_\mathrm{CiC} = 33$, $\mu^*_\mathrm{CO_2} = 81$, $\sigma^*_\mathrm{CiC} = 1.55$, $\sigma^*_\mathrm{CO_2} = 1.16$), their results can be reproduced (apart from minor differences due to rounding), as shown in fig. 1.

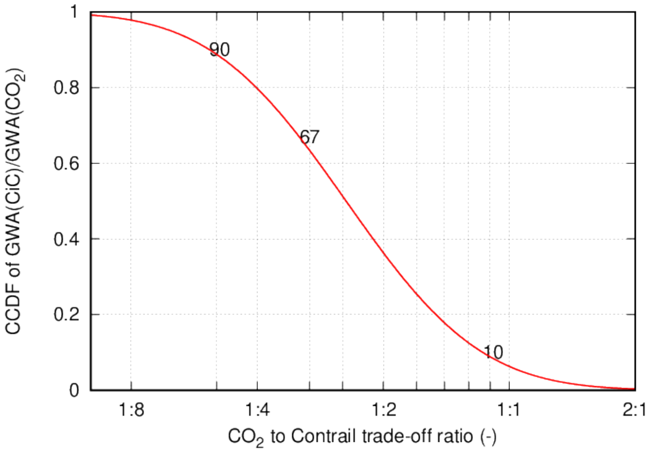

Figure 1. Complementary cumulative distribution function of the ratio of $\mathrm{GWA_{CiC}/GWA_{CO_2}}$ as in the paper of PGP. The chosen time horizon for GWA is 100 years. The same labels have been used as in PGP at 90, 67, and 10%. The exact meaning of the values on the x-axis is given in sect. 3.3.

In Fig. 1 the x-axis has been labeled, instead with real numbers x, with ratios in the form $1:n$ to be consistent with the formulation of PGP. The mitigation effort ($|\Delta_{\mathrm{CiC}}|$) increases with n. The interpretation of the red curve is as stated above: it shows for each value on the x-axis the probability that $\mathrm{GWA_{CiC}/GWA_{CO_2}}$ equals or exceeds this value. For instance, it is highly certain that $\mathrm{GWA_{CiC}/GWA_{CO_2}}$ is at least equal to $x = 0.125 = 1:8$ ($\overline{F_{\mathrm{X}}}(0.125)$ is close to unity). Similarly, it is almost certain that $\mathrm{GWA_{CiC}/GWA_{CO_2}}$ does not exceed $x = 2 = 2:1$ ($\overline{F_{\mathrm{X}}}(2)$ is close to zero). The shape of the curve shows that between these extremes the probability that $\mathrm{GWA_{CiC}/GWA_{CO_2}}$ is at least equal to a certain value x or $1:n$ decreases with increasing x ($1:n$). This implies that, if a quite large mitigation effort, e.g., with a trade-off ratio of $1:8$, would by spent, the probability of success would be very high since the actual GWA ratio very probably exceeds $1:8$. If the actual GWA ratio would indeed be $1:1$, which has a probability of less than 10%, a small mitigation effort that avoids one unit of CiC at the expense on one unit of CO$_2$, would just suffice to render the effort successful. The meaning of "unit" will be clarified in sect. 3.3.

Note, that proper usage of the result in terms of the GWA ratios requires that the contrail reduction and the simultaneous increase of CO$_2$ need to be expressed in terms of the corresponding GWA metrics. This is not clearly explained by PGP. They write instead "The 1:N ratio describes ... an N percentage reduction in the non-CO$_2$ cancels a 1% increase in CO$_2$ emissions." It remains unclear to what these percentages refer to. In their methods section "Risk curve" the description seems correct, but their figure caption to figure 3 is unclear in this respect as well, when it describes trade-offs as "CO$_2$ increase (%): contrail reduction (%)". The reference of these increases and reductions is not clear, and a reader could get the impression that the result could be applied to single flights (assuming, for instance, that "percent reduction" could mean the reduction of emitted mass or their subsequent impact during a single flight), which it certainly cannot. PGP indeed state that GWA could be applied to single flights, however the question is how this could be achieved in the short time frame available for flight planning and with sufficient precision. For single flights, situation-dependent variability (e.g., of the synoptic situation) will lead to individual GWAs and thus different CCDFs with probably wide variability of shapes, which renders the method impracticable. For more discussion on this, see sect. 4.1.

Finally, for the mitigation of contrail-induced climate warming, it is not sufficient to compare the contrail GWA merely against the $\mathrm{CO_2}$ GWA, since rerouting that requires more fuel leads to increased emissions not only of carbon dioxide, but of all other gaseous non-$\mathrm{CO_2}$ effects as well. A proper treatment, consistent with the method of PGP, requires therefore to replace the $\mathrm{GWA_{CO_2}}$ by the sum of the GWAs of the gaseous non-$\mathrm{CO_2}$ effects, which will necessarily change the curve shown in fig. 1. An example is given below in sect. 4.3.

3 An alternative formulation of trade-off and risk

The primary purpose of this section is to derive the mathematics of trade-offs and corresponding risks in a clear and transparent way, where the eventually resulting equation is explained and justified.

3.1 Trade-off ratio as a negative derivative

A trade-off is the consequence of interdependencies in a system in such a way, that an improvement with respect to the target effect in one component leads to deterioration in another one. A familiar example is presented by the Pareto-curve of eco-efficient routing (e.g., Matthes et al., 2020, their figure 2), which indicates how a lessened impact on climate comes at additional operational cost. Mathematically, such a change of a pair of interdependent components can be described by ΔX and ΔY, and once their ratio is negative, there is a trade-off. As the Δ-signs indicate, the consideration needs defining two states, an initial or reference state and one where interdependent changes in two components X and Y are assumed (or have actually occurred). As the example of the Pareto-front shows, the ratio $\Delta X/\Delta Y$ changes along the front and is by no means a constant. The same holds, if other interdependencies are considered, for instance the $\mathrm{NO_x}$ vs. fuel trade-off. Fuel savings are possible by allowing higher flame temperatures in the combustor, which, unfortunately, enhances $\mathrm{NO_x}$ formation. The corresponding $\Delta X/\Delta Y$ is not a physical constant, rather it certainly depends on the concrete technical realisation of the combustor. Another example is the difference between east- and westbound flights over the North Atlantic which have, due to the jet-stream influence, quite different Pareto-fronts (e.g. Grewe et al., 2017c), and thus non-constant trade-off ratios.

The concrete trade-off ratio depends on the concrete situation and cannot be given in general.

3.2 Trade-off mathematics

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 climate metrics (incl. GWP and $\mathrm{GWA_C}$) 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 are useful 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 useful, 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.

One can imagine that in 2018 an operational or technical measure would have been permanently in force that would have led to changed ERF values overall. Note that the subjunctive mode is necessary here, as an impossible situation is imagined. 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 and 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:

$$M_\mathrm{C} = \Phi(\mathrm{ERF}_\mathrm{C};\Pi_\mathrm{C}), \tag{5}$$

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

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

$$M'_\mathrm{C} = \Phi(\mathrm{ERF'}_\mathrm{C};\Pi_\mathrm{C}). \tag{6}$$

If the operator Φ is linear, then

$$M'_\mathrm{C} - M_\mathrm{C} = \Phi(\mathrm{ERF'}_\mathrm{C};\Pi_\mathrm{C}) - \Phi(\mathrm{ERF}_\mathrm{C};\Pi_\mathrm{C}) = \frac{\mathrm{d}\,\Phi(\mathrm{ERF}_\mathrm{C};\Pi_\mathrm{C})}{\mathrm{d}\,\mathrm{ERF}_\mathrm{C}}(\mathrm{ERF}'_\mathrm{C} - \mathrm{ERF}_\mathrm{C}) =: \mathbf{D}\,\Phi(\mathrm{C})\,\Delta\mathrm{ERF}_\mathrm{C}, \tag{7}$$

where the symbol $\mathbf{D}\,\Phi$ 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, both derivatives are 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.

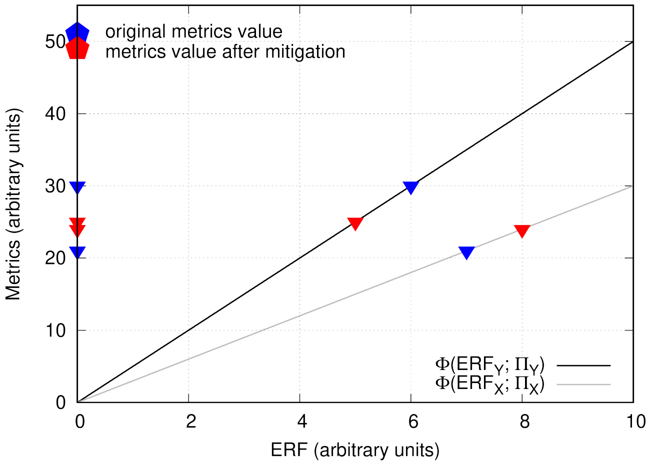

Figure 2. Metrics $M = \Phi(\mathrm{ERF};\Pi)$ as function of ERF. The two functions Φ (black and grey, assuming linear dependence of Φ on ERF) have different slopes, indicating different sensitivity of the metrics to the ERF values. Two pairs of ERF values (blue and red triangles) represent current (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 $\mathrm{ERF_Y}$ is reduced along a steeper slope while $\mathrm{ERF_X}$ 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.

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

$$(M'_\mathrm{X} - M_\mathrm{X}) + (M'_\mathrm{Y} - M_\mathrm{Y}) \leq 0 \tag{8}$$

and implies (see fig. 2 for an illustration)

$$\mathbf{D}\,\Phi(\mathrm{X})\,\Delta\mathrm{ERF_X} + \mathbf{D}\,\Phi(\mathrm{Y})\,\Delta\mathrm{ERF_Y} \leq 0, \tag{9}$$

which is equivalent to

$$\frac{\mathbf{D}\,\Phi(\mathrm{X})}{\mathbf{D}\,\Phi(\mathrm{Y})} \leq -\frac{\Delta\mathrm{ERF_Y}}{\Delta\mathrm{ERF_X}}. \tag{10}$$

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

$$\frac{\mathbf{D}\,\Phi(\mathrm{Y})}{\mathbf{D}\,\Phi(\mathrm{X})} \geq \frac{1}{\frac{|\Delta\mathrm{ERF_Y}|}{\Delta\mathrm{ERF_X}}}. \tag{11}$$

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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 can be postulated and can thus be considered to be represented by a certain number. Let us thus assume that in a certain mitigation measure one unit of increase of $\mathrm{ERF_X}$ allows a reduction of $\mathrm{ERF_Y}$ by n units. Then the condition for a positive outcome is:

$$\frac{\mathbf{D}\,\Phi(\mathrm{Y})}{\mathbf{D}\,\Phi(\mathrm{X})} \geq \frac{1}{n}, \tag{12}$$

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 or an equivalence ratio 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. 2). 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 statement that "clearly the most pressing need is to firmly establish the ERF calculations" turns out unjustified.

In the next section I will give a concrete example.

3.3 An example using GWA

In this section we choose for $\Phi(\mathrm{ERF_C};\Pi_\mathrm{C})$ 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)

$$\mathrm{AGWP_C}(H) = \int_0^H A_\mathrm{C}\,\mathrm{I_C}(t)\,\mathrm{d}t = A_\mathrm{C}\int_0^H \mathrm{I_C}(t)\,\mathrm{d}t \tag{13}$$

where A_C is the effective radiative forcing per kg increase in the component C in the atmosphere, that is, $\mathrm{ERF_C} = A_\mathrm{C}\cdot m_\mathrm{C}$, where m_C is the emitted mass of C due to the considered activity that leads from $\mathrm{AGWP_C}$ to $\mathrm{GWA_C}$. That is, we use $\mathrm{GWA_C} = M_\mathrm{C} = \Phi(\mathrm{ERF_C};\Pi_\mathrm{C}) = \mathrm{ERF_C}\int \mathrm{I_C}(t;\Pi_\mathrm{C})\,\mathrm{d}t$. $\mathrm{I_C}(t;\Pi_\mathrm{C})$ is the impulse response function of component C. $\mathrm{I_C}(t)$ has a simple exponential form for, e.g., contrail cirrus, ozone and methane, that is, $\exp(-t/\alpha_\mathrm{C})$ (that is, the parameter $\Pi_\mathrm{C} = \alpha_\mathrm{C}$ is the atmospheric lifetime of the perturbation of C). For $\mathrm{CO_2}$ the expression must include more than one atmospheric decay timescales (usually three), that is, $\Pi_{\mathrm{CO_2}}$ is a parameter vector. Once the horizon H is fixed, the integral over $\mathrm{I_C}(t;\Pi_\mathrm{C})$ has a certain value $K_\mathrm{C}(H)$, that depends on the chosen horizon and which is specific to the component in question. $\mathrm{GWA_C}$ is thus the product $\mathrm{ERF_C}\cdot K_\mathrm{C}(H)$. Thus, the sensitivity factor introduced above (eq. 7) is simply $\mathbf{D}\,\Phi(\mathrm{C}) = K_\mathrm{C}(H)$. The postulate for a climate benefit then reads:

$$K_\mathrm{X}(H)\Delta\mathrm{ERF}_\mathrm{X} + K_\mathrm{Y}(H)\Delta\mathrm{ERF}_\mathrm{Y} \leq 0. \tag{14}$$

Since $K_\mathrm{C}(H) = \mathrm{GWA}_\mathrm{C}/\mathrm{ERF}_\mathrm{C}$ this can be rewritten as

$$\mathrm{GWA}_\mathrm{X}\frac{\Delta\mathrm{ERF}_\mathrm{X}}{\mathrm{ERF}_\mathrm{X}} + \mathrm{GWA}_\mathrm{Y}\frac{\Delta\mathrm{ERF}_\mathrm{Y}}{\mathrm{ERF}_\mathrm{Y}} \leq 0. \tag{15}$$

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

$$\frac{\mathrm{GWA}_\mathrm{Y}}{\mathrm{GWA}_\mathrm{X}} \geq -\frac{\Delta\mathrm{ERF}_\mathrm{X}/\mathrm{ERF}_\mathrm{X}}{\Delta\mathrm{ERF}_\mathrm{Y}/\mathrm{ERF}_\mathrm{Y}} = \frac{\Delta\mathrm{ERF}_\mathrm{X}/\mathrm{ERF}_\mathrm{X}}{|\Delta\mathrm{ERF}_\mathrm{Y}|/\mathrm{ERF}_\mathrm{Y}} = 1 : \frac{|\Delta\mathrm{ERF}_\mathrm{Y}|/\mathrm{ERF}_\mathrm{Y}}{\Delta\mathrm{ERF}_\mathrm{X}/\mathrm{ERF}_\mathrm{X}}. \tag{16}$$

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 figure 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 $|\Delta\mathrm{ERF}_\mathrm{CiC}| = 10 \times \Delta\mathrm{ERF}_{\mathrm{CO}_2}$. To mark a trade-off ratio in PGPs figure 3 it is necessary then to multiply this ratio of absolute changes with the ratio of the uncertain ERFs, for which I assume a lognormal ratio consistent with PGPs assumptions. From this ratio distribution I draw 1000 samples and use them to estimate the percentiles of this disribution. 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. 16, presented as percentiles on the x-axis (blue lines in fig. 3). 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 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.

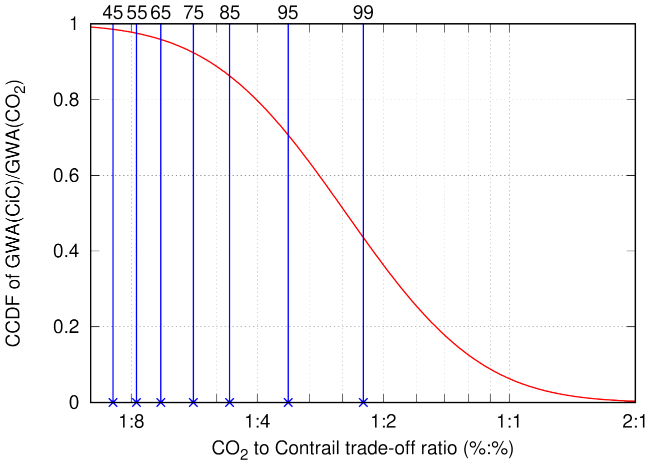

Figure 3. As fig. 1, but illustrated for a case with an absolute trade-off ratio $|\Delta\mathrm{ERF}_{\mathrm{CiC}}| = 10 \times \Delta\mathrm{ERF}_{\mathrm{CO_2}}$, for which the distribution of the corresponding relative trade-off ratio that is needed for the x-axis of PGPs figure 3 is given as percentiles (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.

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

$$\frac{K_{\mathrm{Y}}(H)}{K_{\mathrm{X}}(H)} \geq \frac{1}{|\Delta\mathrm{ERF}_{\mathrm{Y}}|/\Delta\mathrm{ERF}_{\mathrm{X}}} =: 1:n, \tag{17}$$

for which the $1:n$ representation of the x-axis is justified. Recall that the quantities $K_{\mathrm{C}}(H)$ 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).

3.4 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, CO_2. Then let

$$\Delta\mathrm{ERF}_X = \mathrm{ERF}'_{\mathrm{CO_2}} - \mathrm{ERF}_{\mathrm{CO_2}} \quad \text{for CO}_2 \tag{18}$$

$$\Delta\mathrm{ERF}_Y = \mathrm{ERF}'_{\mathrm{CiC}} - \mathrm{ERF}_{\mathrm{CiC}} \quad \text{for contrail cirrus.} \tag{19}$$

In this section we perform the trade-off risk calculation in terms of the equilibrium near-surface temperature change, $\Delta T_{\rm eq}^{\rm X,Y}$, caused by the corresponding effective radiative forcings, that is we set the operator $\Phi_{\rm X,Y}$ simply to the corresponding climate sensitivity factors, such that M_X and M_Y become $\Delta T_{\rm eq}^{\rm X,Y}$. 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:

$$\Delta T_{eq}^{\rm CO_2} = \lambda_{\rm ERF}^{\rm CO_2} \cdot {\rm ERF}_{\rm CO_2}, \quad \Delta T_{eq}^{\rm CiC} = \lambda_{\rm ERF}^{\rm CiC} \cdot {\rm ERF}_{\rm CiC}. \tag{20}$$

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

$$\begin{aligned} \Delta\Delta T_{\rm eq} &= \Delta\Delta T_{eq}^{\rm CO_2} + \Delta\Delta T_{eq}^{\rm CiC} && (21) \\ &= \lambda_{\rm ERF}^{\rm CO_2}({\rm ERF}'_{\rm CO_2} - {\rm ERF}_{\rm CO_2}) + \lambda_{\rm ERF}^{\rm CiC}({\rm ERF}'_{\rm CiC} - {\rm ERF}_{\rm CiC}). && (22) \end{aligned}$$

Whether the change $\Delta\Delta T_{\rm eq}$ 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 we know what we do, that is, if we know the changes ΔERF for both components, contrail cirrus and $\rm CO_2$. Before it is possible to estimate how ΔERF will change as a result of the mitigation, this mitigation measure should be avoided. Once ΔERF can be estimated, the sign of $\Delta\Delta T_{\rm eq}$ can be computed without difficulty as soon as the conversion factors are known. Indeed, the result is good for climate (that is $\Delta\Delta T_{\rm eq} \leq 0$) as soon as $-\Delta\,{\rm ERF}_{\rm CiC} \geq (\lambda_{\rm ERF}^{\rm CO_2}/\lambda_{\rm ERF}^{\rm CiC})\Delta\,{\rm ERF}_{\rm CO_2} = 2.63 \times \Delta\,{\rm ERF}_{\rm CO_2}$, using the climate sensitivity factors from Bickel et al. (2025). So far, no risk at all appears in the calculation.

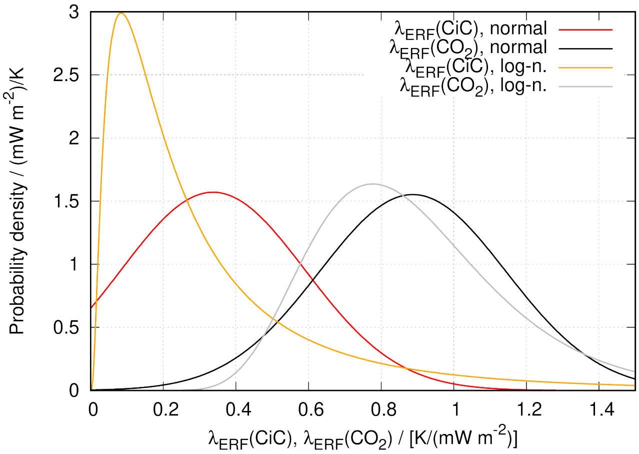

Figure 4. Probability density functions for the unknown true values of $\lambda_{\rm ERF}$ for CO_2 and contrail induced cirrus (CiC) using best estimates and 90% confidence intervals from Bickel et al. (2025). Two model distributions for the underlying uncertainty are used, the normal distribution (red and orange curves), which are symmetric as the error bars in Bickel et al. (2025) suggest, and the log-normal distribution used to avoid the possibility of negative values.

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

$$\lambda_{\rm ERF}^{\rm CO_2} = 0.887 \pm 0.257; \quad \lambda_{\rm ERF}^{\rm CiC} = 0.337 \pm 0.254. \tag{23}$$

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, we prefer (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. 4. The geometric standard deviations and means are then (no units):

$$\sigma^*_\lambda(\mathrm{CO_2}) = 1.35; \quad \mu^*_\lambda(\mathrm{CO_2}) = 0.85 \tag{24}$$

$$\sigma^*_\lambda(\mathrm{CiC}) = 2.67; \quad \mu^*_\lambda(\mathrm{CiC}) = 0.22 \tag{25}$$

The resulting uncertainty distributions are presented in fig. 4 This statistical model does now allow a risk analysis.

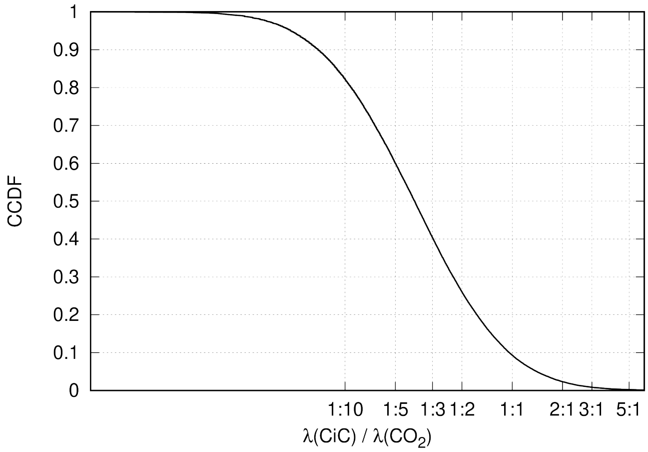

Figure 5. Risk curve in the form of PGP's one.

As stated above, if we 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. 5, similarly to the plots of PGP. The interpretation is as indicated in the previous paragraph. 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 under-represented 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 $\Delta T_{eq}^{\mathrm{C}} = \lambda_{\mathrm{RF}}^{\mathrm{C}} \mathrm{RF}^{\mathrm{C}}$ 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

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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.

4 Discussion

4.1 What are the factors in the trade-off equation?

Although eqs. 1 and 3 seem straightforward, simple and easy to understand, there are hidden issues that ask for discussion. One issue is, that GWP in eq. 1 is neither additive nor extensive. However, using the definition $\mathrm{GWP}_{\mathrm{CH}_4} = \mathrm{AGWP}_{\mathrm{CH}_4}/\mathrm{AGWP}_{\mathrm{CO}_2}$ and rewriting the inequality in the following form:

$$-\Delta\mathrm{CH}_4\,\mathrm{AGWP}_{\mathrm{CH}_4} \geq \Delta\mathrm{CO}_2\,\mathrm{AGWP}_{\mathrm{CO}_2}, \tag{26}$$

both sides of the inequality become additive and extensive quantities (in fact, these are GWAs). In this form the equation is almost trivial, but still, since the AGWPs are uncertain, there is a risk involved in the CH_4 vs. CO_2 trade-off. We see here, however, that if eq. 3 is written (naively) in an analogous form to eq. 1, the rhs of the inequality must have a different meaning to the rhs of eq. 1. The quantities $\Delta\mathrm{C}$ are masses or mass fluxes in eq. 1, but in eq. 3 they are not and the meaning of $\Delta\mathrm{C}$ is not immediately clear. The correct form and actual meaning of $\Delta\mathrm{C}$ (and similar quantities) in eq. 3 is given in eq. 16. This interpretation can indeed be found once in the text of PGP ("meaning that a 3% reduction in contrail forcing..."), but at other locations the $\Delta\mathrm{C}$ seems to be rather the changed amount of an emission (mass). The interpretation as either masses or forcings is even mixed in the caption to their figure 3: "...trade-off ratio of 1% added CO_2 to reduce contrail forcing by 5%". Whichever way you look at it, it ultimately turns out that the result even in its correct form, that is eq. 16, is not applicable for a risk analysis, since both sides contain uncertain quantities.

A further question is, whether $\Delta\mathrm{C}$ in eq. 1 or the risk-analysis involving the GWAs may refer to a single flight. AGWP is essentially a global long-term averaged quantity which makes it questionable to interpret $\Delta\mathrm{C}$ as referring to single flights. In the same way, ERF values as in eq. 16 refer to at least annual averages, ERFs for single flights would be much more uncertain than the annual averages due to situation-dependent feedbacks, partly occuring after and off-side the flight track. This problem does not arise for CO_2 because of its extremely long residence time in the atmosphere. The climate response to a $\Delta\mathrm{CO}_2$ is independent of the location and time of the emission, and thus a long-term global average of the climate response is equivalent to the response of a unit emission at any location and any time.

For short-lived climate forcers like the non-CO_2 effects of aviation the situation is different. The climate response (in terms of RF) of these forcers depends on the synoptic situation and the position of the sun at the location and time of the emission. For instance, the effect of contrails varies widely between night and day (Stuber et al., 2006; Newinger and Burkhardt, 2012), and the effect of NO_x emissions depends on the synoptic situation, concretely, whether the emission is advected either into the polar or tropical direction (Frömming et al., 2021). The climate response for short-lived climate forcers cannot be given in

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terms of ERF for single flights, because of the non-local character of ERF. Similarly, as there is no situation-dependent global warming potential, eq. 1 would make no sense if its ΔX-quantities would be interpreted as quantities that describe single flights. This implies also that a GWA or ERF for single flights makes no sense in a trade-off equation like eq. 16. A single flight cannot be treated using a global exchange-rate or metric. Consequently, eq. 1 only makes sense, if its ΔX factors describe, like GWP or GWA, long-term global averages. The correct form of the risk-analysis in the case involving GWA, eq. 17, includes the lifetime of a perturbation, which may not be a constant for single emissions (for instance, contrails have a wide variety of lifetimes, see Gierens and Vázquez-Navarro, 2018). Thus, the trade-off consideration is not applicable, even in this form, to a single flight.

4.2 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.

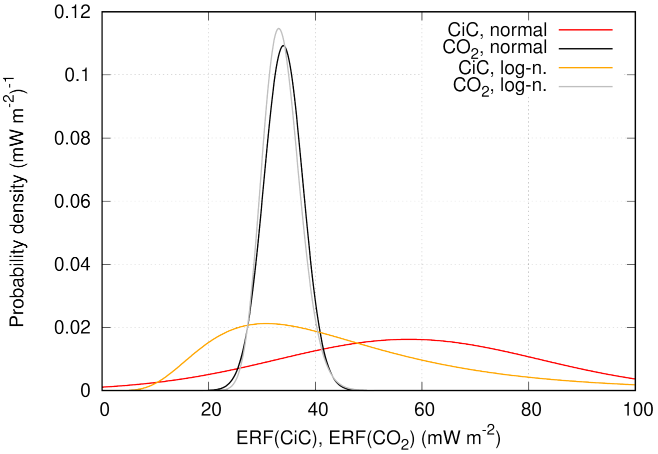

Figure 6. Probability density functions for the unknown true values of ERF for CO_2 and contrail induced cirrus (CiC) using best estimates and 90% confidence intervals from Lee et al. (2021). Two model distributions for the underlying uncertainty are used, the normal distribution (red and orange curves), which are symmetric as the error bars in Lee et al. (2021) suggest, and the log-normal distribution as used by PGP.

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. 6.

385 I have repeated the computation of the risk function for an underlying normal distribution of the GWA uncertainties. For this, I have taken the geometric means and standard daviations from PGPs table and translated them 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 the result must be obtained using a Monte Carlo experiment. The result is presented in fig. 7.

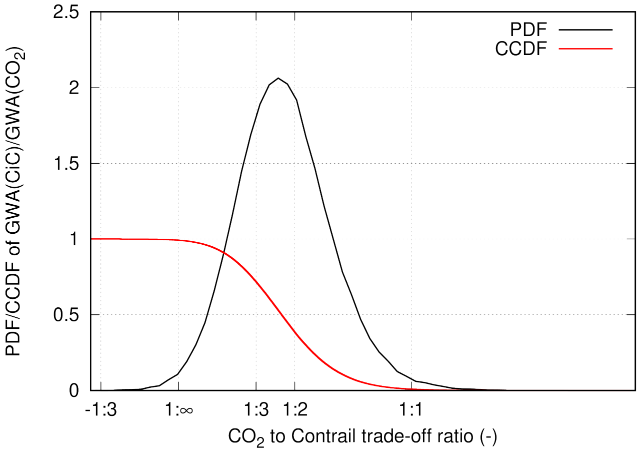

Figure 7. Probability density and CCDF of the GWA ratio for contrails and CO$_2$ for the case of a normal distribution of the uncertainties. The chosen time horizon is 100 years.

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 (fig. 1).

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 resulting 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 $\overline{F}(z)$ cannot be regarded as an objective measure of trade-off risk.

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4.3 Taking into account all gaseous emissions for contrail mitigation

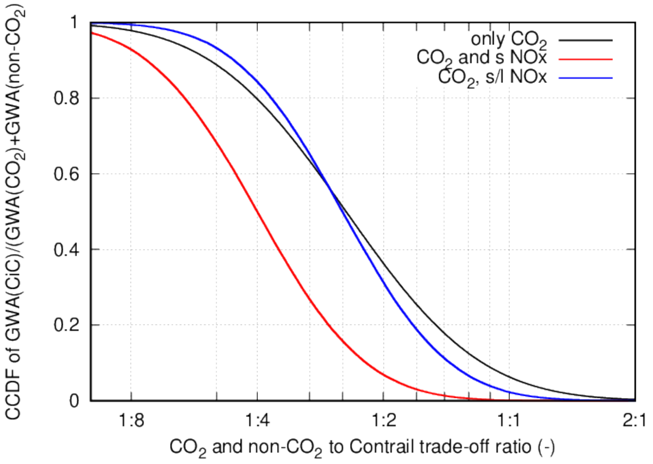

Figure 8. CCDF of the GWA ratio for contrails and CO_2+NO_x for the case of a log-normal distribution of the uncertainties. The red curve represents the addition of the short NO_x (i.e. O_3) effect alone, while the blue curve involves both short- and long NO_x effects in a way that mimics their correlation, that is, their partial cancellation. The chosen time horizon is 100 years.

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. 8. The black curve is just the copy from fig. 1; 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. My 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.

5 Conclusions

In the present paper I have discussed the notions exchange rate, trade-off rate, risk for aviation mitigation measures, and the relation between them. This has been in response and extension to a recent paper (Prather et al., 2025), which, while making strong statements about the low risk of mitigation measures, to my feeling, leaves a couple of important points undiscussed. I hope that the present paper helps to make the involved mathematics more transparent and that the reasoning that leads to the risk formulation becomes clearer. Although the calculations are in the spirit of PGP, and although they come eventually to similar equations, the reasoning that leads to the present formulation is quite different from PGPs argumentation. I summarise the findings of the present study in the following points:

- Exchange rates (equivalence ratios) and trade-off ratios are conceptually different notions, although they may be related. The global warming potential is rather an exchange rate than a trade-off ratio. The same holds for the ratio of a pair of global warming potential per activity (GWA) values.
- Exchange rates are independent of concrete mitigation measures, but an assessment of the success of a concrete action may involve an exchange rate.
- Metrics must be additive and extensive quantities to be appropriate for trade-off considerations.
- Trade-offs occur related to concrete technical or operational measures in systems with interdependencies. Mathematically they can be presented as a derivative or difference quotient with negative value that depends on the particularities of the given technical realisation or operational measure. The actual physical meaning of this difference quotient depends on the choice of the metric that is used to determine whether the respective mitigation measure will be successful or not.
- While reference states, which are for instance described by ERFs, may be uncertain, mitigation measures should result in ERF *changes,* ΔERF, that are principally known to the operator before the mitigation is realised. A mitigation measure with uncertain outcome should not be taken. In trade-off and risk considerations, as proposed here, only ΔERF appears in the equations, not the ERF themselves.
- The ERF change due to a mitigation measure entails a change in any metric into which it may be mapped. If this mapping would be free of uncertainties, no risk would appear. It is the uncertainty of the parameters Π_C of the mapping (the operator Φ_C) that leads to an uncertain change of the selected metrics, and thus induces a risk. The latter can be modelled as a probability density function which ideally should be selected on the basis of physical and statistical arguments.

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- The resulting risk inequality has a ratio of uncertain quantities only on one side. The other side must have well-defined numbers only, with which the CCDF of the uncertain ratio is to be compared. PGPs method leads to uncertain quantities on both sides of the inequality. Hence it is impossible to characterise a certain mitigation measure with a certain number on the ordinate. Thus, PGPs method turns out to be inadequate for its purpose.

The central result of this study is that the actual uncertainties relevant for a trade-off risk assessment lie in the parameters (Π) of the operator (Φ) that is used to map the initial uncertain radiative quantities (RF or ERF) onto the selected metrics. The uncertainties of the radiative quantities are mapped onto uncertainties of the chosen metrics. The trade-off ratio of a concretely planned or taken mitigation measure must be the ratio of absolute changes ($\Delta\mathrm{EFR}$), which need to be known with some precision. They must not be relative changes ($\Delta\mathrm{EFR}/\mathrm{ERF}$), since these still involve uncertainties, and that would leave the method impracticable. If one indeed uses PGPs method, the trade-off ratio must be represented as a distribution of the ratio of the unknown relative ERF changes. For the case of contrail cirrus most of this distribution lies at higher 1:N values than the ratio of absolute ERF changes would suggest, implying a higher risk.

Further conclusions from this paper are:

- For aviation, the statistical basis for a well-founded selection of an uncertainty model of the exchange rates is currently too thin to provide good arguments for a certain statistical model of the uncertainty. Determination of the resulting risk function suffers therefore from a certain degree of arbitrariness.
- Incomplete accounting of uncertainty sources, which is nearly inevitable, causes an underestimation of the eventual trade-off risk. Actually, risk curves are flatter than shown in the present and PGP's examples, as can be seen, for instance, from eq. 4, by representing a larger uncertainty with a larger value of σ^*. How much they are flatter, remains, for the time being, unknown.
- Exchange rates and other metrics generally refer to global and long-term means. This implies that the trade-off ratios must be measured as the effect of concrete actions on the global long-term values. For single flights, this is hardly possible. Thus, proper trade-off considerations are those for an overall concept of mitigation applied for a climatological time period that leads to a quantifiable (measurable) change in the used metrics and exchange rates. To determine such a change needs a climate model or at least a surrogate model.
- For the particular case of contrail avoidance, it is necessary to include the increased amount of all gaseous aviation emissions into the risk-calculation, not only CO_2.

The derivation of trade-off and risk mathematics in this paper is quite different from that of PGP. The interpretation is different as well. Apart from that, the method is not mature enough to base practical decisions on. Important uncertainties are not covered in the calculation and the stochastic model for the uncertainties is close to arbitrary. To my view, there are better methods to guide mitigation decisions, especially for single flights. These methods are based on ensemble weather forecasts, which can be used in flight planning for risk-informed or even risk-optimised strategies (Borella et al., 2026). Furthermore, inspection of weather ensembles shows when forecasts are more or less trustworthy for mitigation actions and how situations with reliable forecasts can be distinguished from those with uncertain weather prediction (Hanst et al., 2025; von Koslowski and Gierens, 2026). Finally, PGPs and the current work should give arguments for more, urgently necessary, research (e.g. to broaden the thin statistical basis or to use other methods and models to explore forcing and feedback mechanisms basic to key metrics).

Appendix A: Numbers used in the calculations

For the calculation of the curves in fig. 7 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. 8 the following quantities have been used:
$\mu^*_{\mathrm{CiC}} = 33.$, $\sigma^*_{\mathrm{CiC}} = 1.55$,
$\mu^*_{\mathrm{sNOx}} = 49.$, $\sigma^*_{\mathrm{sNOx}} = 1.45$,
$\mu^*_{\mathrm{lNOx}} = -30.17$, $\sigma^*_{\mathrm{lNOx}} = 1.13$,
$\mu^*_{\mathrm{CO_2}} = 81.$, $\sigma^*_{\mathrm{CO_2}} = 1.16$.
The starred quantities are geometric means and standard deviations. The correlation between the NOx effects has been modelled by using a single GWA distribution with
$\mu^*_{\mathrm{NOx}} = \mu^*_{\mathrm{sNOx}}\mu^*_{\mathrm{lNOx}} = 1.62$, $\sigma^2_{\mathrm{NOx}} = \sigma^2_{\mathrm{sNOx}} + \sigma^2_{\mathrm{lNOx}}$, thus $\sigma^*_{\mathrm{NOx}} = \exp(\sigma_{\mathrm{NOx}}) = 1.48$.

Author contributions. KG has derived all equations, performed analytical and numerical calculations, written the text and plotted the figures.

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