Distinctive Efficacies of the Components Contributing to Total Aviation Climate Impact

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ABSTRACT: Separate climate sensitivity simulations were run for all important non-CO_2 radiative forcing contributions from aviation (except for contrail cirrus), aiming at the quantification of an individual efficacy parameter for each component. All simulations were performed with the same climate model, E39A. The necessity to scale the original perturbations complicates a straightforward determination of efficacy values, particularly for aviation ozone. The results presented here indicate that a radiative forcing from water vapour increase caused by supersonic aviation would have a similar efficacy than CO_2. Ozone changes induced by subsonic aviation and methane changes appear to have an efficacy larger than CO_2, but the enhancement is moderate (~1.05). For line-shaped contrails we find an efficacy substantially smaller (~0.6) than CO_2 in agreement with previous results. The (small) water vapour increase expected from subsonic aviation shows reduced efficacy (~0.7), too. Similar studies with other climate models are desirable in view of probable model dependency.

1 INTRODUCTION

Aviation impacts on climate in a variety of ways. Radiatively active atmospheric trace gases are changed either directly by aircraft emissions (e.g., CO_2, water vapour) or indirectly (e.g., O_3, CH_4) if atmospheric chemistry is modified by emitting reactive components such as NO_x or aerosols. A further change of the Earth's radiative balance is caused by emissions (water vapour, aerosols) that modify cloudiness, e.g., cirrus coverage and optical properties. According to well-established IPCC practice, all these climate impact components have been compared, quantitatively, in terms of their radiative forcing (e.g., Penner et al., 1999; Lee et al., 2009). In order to account for the differential lifetime of the various tracers when assessing their integrated future impact, more sophisticated metrics such as the Global Warming Potential or the Global Temperature Potential (Fuglestvedt et al., 2009) have to be used which, however, are also calculated based on the radiative forcing. The fundamental role of radiative forcing (RF) originates from the empirical equation

$$\Delta T_{sfc} = \lambda \cdot RF \quad (1)$$

linking RF linearly to the equilibrium change of global mean surface temperature (ΔT_{sfc}) through an assumed constant, the climate sensitivity parameter λ. There has been mounting evidence that, in particular in case of non-homogeneous perturbations (e.g., Joshi et al., 2003), individual climate sensitivity parameters ($\lambda^{(i)}$) different from the basic climate sensitivity due to a homogeneous CO_2 increase ($\lambda^{(CO2)}$) may emerge. Hansen et al. (2005) have proposed to define efficacy parameters ($r^{(i)}$) for such perturbations, retaining the relation given by Eq. (1) in a more comprehensive expression:

$$\Delta T_{sfc} = \lambda^{(i)} \cdot RF = r^{(i)} \cdot \lambda^{(CO2)} \cdot RF \quad (2).$$

Hereafter we will present results from climate sensitivity simulations driven by aviation related RFs (from aviation induced ozone, methane, water vapour, contrails), in an attempt to assign unique efficacy parameters to such forcings. This extends earlier efforts (Ponater et al, 2006, 2007) that lacked consistency in the sense that results were compiled from various model systems. Here, all

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simulations have been run with the ECHAM4/ATTILA (E39A) model system described by Stenke et al. (2008). This model involves enhanced vertical resolution around the tropopause and a Lagrangian advection scheme for water vapour and cloud water which makes it especially suitable to describe forcings and feedbacks in the upper troposphere and lower stratosphere region.

2 THE SCALING PROBLEM

As shown by Lee et al. (2009), an estimate of total RF from aviation for the year 2005 conditions amounts to about 50 mW/m^2. (Note that this value excludes contrail cirrus, for which a reliable RF best estimate has not yet been provided. Thus, this effect is not covered in the present paper either). Individual contributions to the total aviation RF remain generally lower than 30 mW/m^2. Forcings of this magnitude are too small to cause a statistically significant temperature signal in equilibrium climate change simulations and to derive robust values of the climate sensitivity parameter and the efficacy according to Eq. (1, 2). Thus, strong scaling of respective emissions or concentration changes is unavoidable in order to ensure significant signals. Conceptually, the climate sensitivity parameters ($\lambda^{(i)}$) in Eq. (2) are expected to be independent from the magnitude of the forcing, so RF scaling ought to be a straightforward procedure. Moderate deviations from this basic assumption have been pointed out even in the CO_2 case for a number of climate models (e.g., Senior and Mitchell, 2000; Boer and Yu, 2003; Hansen et al., 2005). Nevertheless, calculation and attribution of distinctive efficacies $r^{(i)}$ remains possible as long as their deviation from unity is sufficiently large to neglect a small uncertainty in $\lambda^{(CO2)}$. Indeed, Hansen et al. (2005) defined $\lambda^{(CO2)}$ with respect to a 50% CO_2 increase over a (pre-industrial) background concentration of 291 ppmv as their reference, paying little heed to the magnitude deviation of some other forcings when interpreting their efficacy values for a larger number of effects. In agreement with previous results, the E39A model used for the simulations reported hereafter shows a relatively small variability of $\lambda^{(CO2)}$ with increasing RF: Its value is 0.70, 0.72, and 0.74 K/Wm^{-2} as RF(CO_2) increases from 1.01 over 3.79 to 6.16 W/m^2.

However, as pointed out in a companion study to the present paper (Ponater et al., this volume), it is not guaranteed that such robustness of λ exists for other forcing agents as well. Equilibrium climate change simulations with E39A, forced by ozone change patterns resulting from transport emissions, yielded a climate sensitivity increase of up to 30 % for the same pattern if the forcing was heavily scaled. Hence, in that case the efficacy proved to be more dependent on the scaling of a pattern than on its structure. While the problem could be solved by diagnostic analysis and more simulations, the respective experience suggests to limit the amount of scaling, keeping the RF at values around 1 W/m^2 (or smaller). A less welcome side effect of this decision to restrict the scaling factors is that the regression method for deriving the RF and the climate sensitivity (Gregory et al., 2004; Hansen et al., 2005) can no longer be applied due to an insufficient signal to noise ratio. However, it will be shown here that useful results can be obtained on the basis of the classical IPCC definition of RF (stratosphere adjusted radiative forcing) and the associated $\lambda^{(i)}$, and $r^{(i)}$ values.

3 RESULTS

3.1 *Simulation dedicated to individual aviation forcing components*

Table 1 lists the relevant parameters for each simulation run with the E39A climate model for this study. The climate sensitivity of a CO_2 increase by 72.3 ppmv (yielding about 1 W/m^2 radiative forcing) is used as a reference, as in the simulations dedicated to methane increase, aviation water vapour increase, and contrails forcings were scaled to a similar magnitude. Note that this means a slight deviation from the way the CO_2 reference value was reached in the companion study dealing with transport related ozone increase (Ponater et al., this volume). The difference is insignificant, however: The climate sensitivity of a 1 W/m^2 CO_2 radiative forcing results as 0.696 K/Wm^{-2} with an estimated 95 % confidence interval of 0.02 K/Wm^{-2}, while the climate sensitivity of CO_2 approximated via the nonlinear fit applied in that companion study is 0.692 K/Wm^{-2}. We further recall that the efficacy of aviation ozone according to Ponater et al., this volume, is about 1.05. This is close to the values directly derived from the two aviation ozone simulations (O3 and O4, using a scaling factor of 50 and 100, respectively) as given Table 1.

	RF_{adj}	ΔT_{sfc}	λ_{adj}	r_{adj}
CO_2 (1 W/m^2)	1.010	0.703	0.696	1
OZavi (30) – O1	0.540	-	-	-
OZavi (40) – O2	0.704	-	-	-
OZavi (50) – O3	0.862	0.617	0.712	1.02
OZavi (100) – O4	1.593	1.167	0.733	1.05
CH_4 (1 W/m^2)	1.053	0.760	0.722	1.04
CH_4 (2 W/m^2)	2.123	1.576	0.742	1.07
Contrails (80, τ =0.3) – C1	0.609	-	-	-
Contrails (80, τ =0.4) – C2	0.833	0.385	0.462	0.66
Contrails (100, τ =0.3) – C3	0.694	0.297	0.427	0.61
Contrails (100, τ =0.4) – C4	0.928	0.383	0.413	0.59
WatVap_avia_sub (750) – H1	0.442	0.223	0.505	0.72
WatVap_avia_sub (1000) – H2	0.555	0.273	0.492	0.71
WatVap_avia_super (20) – HS	0.585	0.428	0.732	1.05
	[Wm^{-2}]	[K]	[K/Wm^{-2}]	

Table 1: Radiative forcing, global mean surface temperature change, climate sensitivity, and efficacy as found in equilibrium climate change simulations with the E39A model. Forcing types are a homogeneous CO_2 increase, the aviation ozone change pattern (OZavi) as given by Hoor et al. (2009), scaled by various factors, a homogeneous CH_4 increase, scaled contrails, and two patterns of aviation induced water vapour increase (see text). In case of the O1, O2, and C1 perturbations, only the stratosphere adjusted radiative forcing (RF_{adj}) was calculated.

Two simulations were performed with two different amounts of homogeneous CH_4 concentration increase to yield either about 1 W/m^2 (+3.11 ppmv) or about 2 W/m^2 (+8.6 ppmv) radiative forcing, respectively. Similar to the CO_2 case, the climate sensitivity of a methane perturbation shows only little dependency on the scaling. The moderate efficacy enhancement of CH_4 versus CO_2 changes is consistent with results reported by Hansen et al. (2005), but there have also been examples of climate models with a CH_4 efficacy smaller than that of CO_2 (Berntsen et al., 2005).

When based on a realistic air traffic density, line-shaped contrails provide only a small radiative forcing (< 15 mW/m^2), hence their amount must be scaled substantially. In the only study that has attempted to estimate an efficacy of contrail forcing before (Ponater et al., 2005), a 2050 aviation inventory was scaled by a factor 20, still yielding a radiative forcing as low as 0.2 W/m^2. In that study the contrail optical depth was not scaled, rather the varying optical depth values (yielding a mean around 0.1) from the contrail parameterisation scheme of Ponater et al. (2002) were retained. This resulted in a marginally significant surface temperature response just sufficient for the purpose of deriving an interpretable efficacy change. Even higher scaling of air traffic density can hardly be recommended, as the contrail coverage pattern may be influenced by excessive scaling as soon as saturation effects for certain regions show up. Hence, for the contrail simulations discussed in this study (Table 1) we decided to scale both air traffic density (contrail coverage) and contrail optical depth in order to reach a larger global contrail radiative forcing around 1 W/m^2. The basic inventory was the same as in Ponater et al. (2002), referring to 1992 aviation density, which was scaled by factors of 80 or 100, while contrail optical depth τ was prescribed to a uniform value of 0.3 or 0.4.

The three contrail driven equilibrium climate change simulations C2, C3, and C4 (Table 1), slightly varying with respect to the choice of scaling, all indicated a similar climate sensitivity parameter around 0.45 K/Wm^{-2}, suggesting that the resulting efficacy of about 0.6 has some degree of robustness. The value also agrees with the one estimated by Ponater et al. (2005) with a (slightly) different climate model and, as explained above, a somewhat different simulation setup. In view of the higher degree of model dependency for the efficacy parameter that has been found in studies dealing with, e.g., ozone change patterns (Joshi et al., 2003; Berntsen et al., 2005), the indications for a substantially reduced efficacy of contrails are strong indeed.

Two simulations for the present study (H1, H2, Table 1) were dedicated to the water vapour change induced by subsonic aviation. The respective concentration increase pattern is characterised by a distinct maximum in the northern hemisphere lowermost stratosphere (Ponater et al., 2006, their Fig. 3). Typical radiative forcings of a perturbation of this magnitude are very small (below 2 mW/m^2 for present day aviation, Lee et al., 2009), and a large scaling has to be applied in order to increase the respective response in equilibrium climate change simulations to acceptable levels of statistical significance. The simulations H1 and H2 consistently suggest an efficacy substantially smaller than the CO_2 reference for this type of forcing. The estimated value is about 0.7, which does not agree with the efficacy suggested in Ponater et al. (2006) for aviation water vapour (1.14). The latter value was, however, derived from a water vapour concentration change pattern induced by a hypothetical supersonic air fleet in the stratosphere (Søvde et al., 2007), which is characterised by a different structure and a much higher basic radiative forcing of around 35 mW/m^2 (Myhre et al., 2009). In order to confirm whether the different concentration change pattern causes the difference in efficacies we repeated with E39A the simulation forced by the supersonic aviation water vapour increase scaled with a factor 20 (HS, Table 1). The respective efficacy parameter is 1.05, which is hardly distinguishable from 1 in a statistical sense, given the relatively small forcing of 0.585 W/m^2.

Summarizing, there are at least two contributions to aircraft climate impact whose forcing may be associated with an efficacy significantly different from unity, line-shaped contrails and water vapour induced by subsonic aviation.

3.2 *Simulations dedicated to forcings from combined individual components*

The usefulness of introducing distinctive efficacies in assessment studies would greatly increase if they can serve as linear weighting factors in case that the response to a combined perturbation (e.g., aviation total impact) is to be derived from the individual response components.

$$\Delta T_{sfc,comb} = r_{comb} \bullet \lambda^{(CO2)} \bullet RF_{comb} \quad ; \quad r_{comb} = \sum(RF^{(i)} \bullet r^{(i)}) / \sum RF^{(i)} \quad ; \quad RF_{comb} = \sum RF^{(i)} \quad (3)$$

This possibility was explored by some simulations forced by more than one of the individual impact contributions (Table 2). Our guideline in choosing appropriate combinations has been not to diverge too far from the standard. For this purpose perturbations with smaller forcing had to be employed (O1, O2, C1, Table 1), for which no dedicated efficacy values from individual simulations had been determined. However, this investigation was built on the hypothesis of unique efficacies for each component anyway, which were assumed according to the last section: 1.05 for water vapour from supersonics and ozone, 0.6 for contrails, and 0.7 for water vapour from subsonics.

	RF_{adj}	ΔT_{sfc}	λ_{adj}	r_{adj}	$r_{adj\ (comb)}$
CO_2 (1 W/m^2)	1.010	0.703	0.696	1	-
O1 + C1	1.122 (98%)	0.683	0.609	0.86	0.83
O2 + C3	1.409 (100%)	0.854	0.606	0.87	0.82
O1 + H1	0.983 (100%)	0.609	0.620	0.89	0.89
O2 + HS	1.294 (100%)	0.994	0.768	1.10	1.05
C1 + H1	1.037 (98%)	0.494	0.476	0.68	0.65
C1 + HS	1.201 (100%)	0.716	0.596	0.86	0.82
C1 + O1 + H1	1.577 (99%)	0.935	0.593	0.85	0.79
	[Wm^{-2}]	[K]	[K/Wm^{-2}]		

Table 2: Radiative Forcing, surface temperature response, climate sensitivity, and efficacy of simulations using more than one aviation impact components. The designations in the 1st column refer to aviation ozone (O), contrail (C), and aviation water vapour (H) perturbations, whose individual forcing and response parameters are given in Table 1. 4th column is the efficacy derived from the actual λ_{adj} values, 5th column the efficacy reached through linear combination according to Equation 3 (see text).

Going through Table 2 it can be noted first (2nd column) that the contributing radiative forcings are almost perfectly additive, a necessary precondition for the linearization of efficacies (Eq. 3) to work. Second, the efficacy parameter for the combined perturbation always takes a value between the contributing component efficacies, except for "O2+HS", where both component efficacies are assumed as equal (1.05) and should also be equal to the combined efficacy in an ideal case. However, as all efficacy parameter values are subject to a statistical uncertainty (which I do not give here due to lack of space), this is still an acceptable degree of non-linearity. The efficacy parameter of a combined perturbation calculated by linear combination of the contributing individual efficacy values (Table 2, last column) are close to the efficacy parameters from the actual climate model simulations forced by the combined perturbation, but with a tendency towards underestimation. This can be related to the fact that the simulations driven by the combined perturbations have, in general, larger forcings. As we already know, for most perturbations larger forcing inhibits higher efficacy. All in all, deviations from the linearity concept behind Eq. 1 to 3 appear to be limited for radiative forcings below 1.5 W/m^2. This provides some confidence in using individual efficacies as weighting factors when the respective perturbations and forcings are combined. The method should be suitable even more so for assessing the present-day aviation climate impact.

4 DISCUSSION AND CONCLUSIONS

Evidence of a distinctive efficacy for at least some individual aviation forcing components poses the question, which feedback mechanisms are at the root of such anomalous effects. The reasons may be different from perturbation to perturbation and also different from model to model. This paper restricts to a brief look at the contrail case, for which the efficacy deviates strongest from the CO_2 reference. As mentioned, Ponater et al. (2005) found a quantitatively similar efficacy reduction for contrails in a previous version of the climate model applied here. Their explanation was, that due to the absence of contrail radiative forcing over the Arctic (where there is only little air traffic) the temperature response at these latitudes is weakened. This entails reduced ice-albedo feedback and reduced global climate sensitivity. The same effect is also apparent, but to a less extent, in the E39A simulations presented here (not shown). Further analysis reveals, however, that the radiative feedback of natural clouds to a contrail forcing also significantly deviates in comparison to a respective CO_2 driven simulation.

	λ_{adj}	ΔCRF(sw)	ΔCRF(lw)	ΔCRF	$\Delta CRF/\Delta T_{surf}$
CO_2 (1 Wm-2)	0.696	−0.659	+0.532	−0.127	−0.181
Contrails (80, τ =0.4) – C2	0.462	−0.296	−0.058	−0.354	−0.919
Contrails (100, τ =0.3) – C3	0.423	−0.262	−0.111	−0.373	−1.255
Contrails (100, τ =0.4) – C4	0.413	−0.365	−0.110	−0.475	−1.240
	[K/Wm^{-2}]	[Wm^{-2}]	[Wm^{-2}]	[Wm^{-2}]	[Wm^{-2}/K]

Table 3: Climate sensitivity, shortwave, longwave, and net radiative feedbacks of natural clouds, and the specific net cloud feedback for the E39A equilibrium climate change simulations driven by CO_2 increase and by scaled forcing of line-shaped contrails (see text). The corresponding global mean surface temperature response can be found in Table 1. The radiative feedback of natural clouds has been taken as the difference of the radiative forcing of natural clouds between the respective simulation and the control simulation.

Table 3 presents the radiative feedback related to changes in natural cloudiness for the three contrail simulations already discussed in Section 3.1, together with the CO_2 increase simulation scaled to 1 W/m^2 forcing. The latter exhibits negative cloud feedback in the solar spectrum (i.e., enhanced shortwave cooling) and positive cloud feedback in the terrestrial spectrum (i.e., enhanced longwave warming) yielding a comparatively small net cooling effect. In the contrail driven simulations both shortwave and longwave feedback components are negative, resulting in a stronger negative net feedback. It is notable that in simulations C2, C3, and C4 natural cirrus cloud coverage decreases at latitudes and altitudes where contrails are present, while in the CO_2 driven simulation cirrus cloud coverage increases in the same regions (not shown). As natural cirrus clouds provide a warming of the climate system it is consistent that the climate sensitivity of a perturbation should be reduced if it acts to remove cirrus coverage. The contrails produced by the parameterisation of Ponater et al. (2002) warm the upper troposphere and reduce the relative humidity, which could easily lead to the effect that they offset part of their own positive radiative forcing by allowing less natural cirrus than in an atmosphere without contrails. Whether this is an effect reflecting the role of contrails in the real world correctly must remain an open question at this stage.

It can be concluded that efficacy anomalies for some individual effects of aircraft total climate impact are significant, require further research, and deserve attention when determining the balance of effects in aviation assessment studies. Respective indications are obvious for contrails and should be taken into consideration in forthcoming studies of contrail cirrus (see Burkhardt et al., 2010), as its presumably higher radiative forcing makes knowledge of its efficacy even more relevant. The simulations presented here and in the dedicated paper of Ponater et al., this volume, do not confirm the distinct efficacy increase suggested for aviation ozone by previous studies that used idealized ozone change patterns in extra-tropical latitudes (e.g., Stuber et al., 2005). For all aviation impact components more model studies are clearly required in order to allow more reliable conclusions.

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