Indications of Distinctive Efficacies for Transport Related Ozone Perturbations

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ABSTRACT: Two series of equilibrium climate change simulations forced by ozone change patterns from transport emissions have been performed with two climate models. It is investigated whether radiative forcings like this lead to climate sensitivity and efficacy parameters that are significantly different among each other and from a reference forcing caused by a homogeneous CO_2 increase. Identification of such differences is complicated by an unexpectedly strong dependence of the climate sensitivity on the strength of certain forcing patterns. Efficacy parameters calculated for the radiative forcings due to ozone increases resulting from aviation, shipping, and land transport emissions vary from unity by no more than 10%. Our results confirm earlier studies that hinted at the necessity to weight radiative forcings from different mechanisms individually in assessment studies, according to their efficacy, but more work is necessary before reliable efficacy parameters can be attributed to such forcings.

1 INTRODUCTION

For a quantitative inter-comparison of climate impact components, metrics of climate change are needed. As discussed by Fuglestvedt et al. (2009), some of these (like radiative forcing) are easy to obtain but difficult to observe in nature, while others (like temperature change) are physically more intuitive but usually hard to determine with the required accuracy. Despite known limitations, the concept of the radiative forcing of climate change has become a standard tool in global climate research (e.g., Shine et al., 1990; Forster et al., 2007) and it is still almost indispensable when small contributions to a total climate effect are to be quantified. However, some implicit basic assumptions have to be re-checked if the concept is applied to new forcing components. Distinctly non-homogeneous forcings have proved to be a conceptual challenge, as model simulations indicate that the fundamental semi-empirical equation linking global surface temperature change (ΔT_{sfc}) to global radiative forcing (RF)

$$\Delta T_{sfc} = \lambda \bullet RF \qquad (1)$$

is often not fulfilled with a universal climate sensitivity parameter λ (e.g., Joshi et al., 2003; Cook and Highwood, 2004; Stuber et al., 2005). Hansen et al. (2005) have pointed out that in cases like this it may still be possible to define a component's (i) climate sensitivity parameter $\lambda^{(i)}$, from which an efficacy factors $r^{(i)} = \lambda^{(i)} / \lambda^{(CO2)}$ can be derived, where $\lambda^{(CO2)}$ indiactes the climate sensitivity of a homogeneous CO_2 increase. This approach would modify Eq. (1) to

$$\Delta T_{sfc} = \lambda^{(i)} \bullet RF = r^{(i)} \bullet \lambda^{(CO2)} \bullet RF \qquad (2),$$

retaining a useful link of ΔTsfc and RF if <u>unique</u> component efficacies $r^{(i)}$ can be determined. Note that both Eq. (1) and (2) imply that the climate sensitivity parameter for all forcings (including CO_2) does not depend on the magnitude of RF, i.e., that ΔT_{sfc} is strictly linear in RF. As shown in Hansen et al. (2005), however, even for CO_2 perturbations moderate deviations from this assumption are

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apparent. Hence, in their paper the reference climate sensitivity, $\lambda^{(CO2)}$, has been defined as the climate sensitivity to CO_2 doubling.

Ozone change patterns inferred from precursor emissions of certain transport sectors (aviation, shipping, road traffic) are distinctly non-homogeneous (both horizontally and vertically) and also distinctly different from sector to sector (Hoor et al., 2009). In our study we not only investigated whether different forcing patterns imply the existence of unique efficacies different from unity, but also to which extent the values obtained for $\lambda^{(i)}$ and $r^{(i)}$ are model dependent and method dependent. Moreover, we have checked whether the radiative forcing increases linearly with the amplitude of the ozone change pattern and whether it adds linearly across the sectors

$$RF\,(a \bullet \Delta O3^{(j)}) = a \bullet RF(\Delta O3^{(j)}), \quad RF(\sum \Delta O3^{(j)}) = \sum RF(\Delta O3^{(j)}) \qquad (3a,b),$$

where (j) indicates the three transport sectors mentioned above. Finally, we have also considered whether the temperature response is additive across the sectors:

$$\Delta T_{sfc} = \sum \Delta T_{sfc}^{(j)} \qquad (4)$$

Eq. (4) would be equivalent to requiring that the efficacy parameter of a combination of ozone perturbations can be obtained by linear combination of the respective parameters for individual sectors:

$$r = \sum(RF^{(j)} \bullet r^{(j)}) \,/\, \sum RF^{(j)} \qquad (5)$$

We use the ozone change patterns presented by Hoor et al. (2009) as an non-interactive input to two climate models. The respective radiative forcings according to the IPCC are determined. The perturbations are then scaled to ensure statistical significant results for the equilibrium global temperature response and the radiative forcing according to the regression definition (Gregory et al., 2004). The resulting climate sensitivity and efficacy parameters are discussed with respect to their consistency with equations (1) to (5). The reasons for and consequences of deviations from the simple behaviour are suggested.

2 MODELS AND METHODS

Two models have been used for the simulations, viz., ECHAM4/ATT (Stenke et al., 2008) and the UK Met Office Unified Model (UM) (version HADSM3, Williams et al., 2001). Both are full-scale 3-dimensional climate models that are nonetheless economic enough to run many equilibrium climate change simulations including a slab ocean. Each of the runs is at least 45 years long. The first 20 simulation years (spin-up phase) are used to calculate radiative forcings and climate sensitivity parameters (RF_{greg}, λ_{greg}) from the regression method (Gregory et al., 2004). The climate response (e.g., ΔT_{sfc}) is calculated as the difference between the equilibrium states of a climate sensitivity run and a reference simulation. Radiative forcings according to the IPCC definition ('stratosphere adjusted forcing at the tropopause', RF_{adj}) are determined from an extra one-year simulation with the respective radiation code (Morcrette et al., 1986, for ECHAM; Edwards and Slingo, 1996, for UM).

An essential point is the necessity of scaling the original ozone perturbations because, both, the equilibrium temperature response (ΔTsfc) and the parameters derived from the regression method (RFgreg, λ greg) are associated with a statistical uncertainty that renders any simulation with radiative forcing values smaller than about 0.3 W/m2 useless for calculating significant differences between climate sensitivity or efficacy parameters. This emphasizes the crucial role of the linearity assumption for the radiative forcing concept as described in the introduction. ECHAM/ATT as well as the UM have been run with ozone perturbations scaled by factors of 100 and 500. However, for reasons to be explained in section 3 the number of simulations had to be enhanced for ECHAM/ATT.

3 RESULTS

3.1 *Radiative forcing and its linearity*

The results of the radiative forcing calculations for those simulations performed by both models are summarized in Table 1. The RF values based on the regression method (3rd and 5th column) can only be given with sufficient reliability if the perturbations are scaled.

	ECHAM		*UM*	
	RF_{adj}	RF_{greg}	RF_{adj}	RF_{greg}
CO_2 (doubling)	3.792	3.62	*3.76*	*4.04*
OZavi	0.019	-	*0.015*	-
OZavi (100)	1.593 (82)	1.47	*1.27 (85)*	*1.40*
OZavi (500)	5.730 (295)	5.51	*4.34 (289)*	*4.89*
OZrtr	0.034	-	*0.023*	-
OZrtr (100)	2.646 (77)	2.59	*1.94 (84)*	*2.05*
OZrtr (500)	9.051 (264)	8.32	*6.41 (278)*	*6.70*
OZshi	0.034	-	*0.023*	-
OZshi (100)	2.679 (78)	2.79	*1.93 (84)*	*2.27*
OZshi (500)	9.261 (269)	8.48	*6.36 (276)*	*6.91*
OZsum	0.088	-	*0.061*	-
OZall	0.087 (99%)	-	*0.060 (98%)*	-
OZsum (100)	6.918	6.85	*5.14*	*5.72*
OZall (100)	5.637 (81%)	5.54 (81%)	*4.11 (80%)*	*4.58 (80%)*
	[Wm^{-2}]	[Wm^{-2}]	*[Wm^{-2}]*	*[Wm^{-2}]*

Table 1: Radiative Forcing according to the IPCC definition and according to the regression definition for the scaled ozone perturbations from aviation (avi), road traffic (rtr), and shipping (shi), as calculated with the ECHAM and *UM (marked by italics)* climate models. Values in brackets indicate the enhancement factors for the forcings of the scaled perturbations, or the percentage by which the forcing of the sum of all perturbations [OZall(100)] is reduced compared to the sum of forcings of the individual perturbations [OZsum(100)].

Radiative forcing from CO_2 agrees well between the two models, but ozone forcings are generally larger in ECHAM than in UM. The regression method produces smaller radiative forcings for ECHAM but larger radiative forcings for UM, which may be explained by different feedbacks on the short time-scale (Gregory et al., 2004) for the two participating models. Additivity over the three sectors is almost perfect for the un-scaled ozone perturbations. However, as scaling increases saturation effects show up (particularly in the longwave part of the spectrum), which disturb the linearity in the ozone perturbation/radiative forcing relation. Radiative forcings for the factor 500 scaled patterns exceed the forcing of the un-scaled perturbation only by factors less than 300 in both models. Summarizing, substantial non-linearities in the radiative forcing only occur for excessive scaling.

3.2 *Climate response: model dependence*

Table 2 summarizes, for both participating models, the results of radiative forcing, climate sensitivity, and efficacy as determined using the regression method (RF_{greg}, λ_{greg}, r_{greg}). The reference climate sensitivity for CO_2 doubling is surprisingly similar when compared with model to model differences that have been found elsewhere (e.g., Joshi et al., 2003). However, there is no indication of a universal climate sensitivity parameter for either model. A similar conclusion can be drawn when the values are derived using the IPCC forcings (RF_{adj}, not shown). Moreover, except for the aviation ozone perturbation, the results inhibit a substantial non-linearity of the surface temperature response that is inconsistent with the concept outlined above. For the ECHAM model, in particular, the climate sensitivity and efficacy parameters seem to depend more on the scaling of a pattern than on its spatial structure. A straightforward conclusion about possible efficacy differences for the original (un-scaled) ozone perturbations is thus impossible from the simulations listed in Table 2. Only for aviation ozone these simulations do hint at an efficacy value systematically different from unity; however, in this case ECHAM and UM point in opposite directions, the first model suggesting a higher and the second on a lower efficacy.

	ECHAM				*UM*			
	ΔT_{sfc}	RF_{greg}	λ_{greg}	r_{greg}	ΔT_{sfc}	RF_{greg}	λ_{greg}	r_{greg}
CO_2 (doubling)	2.73	3.62	0.78	1	*3.35*	*4.04*	*0.84*	*1*
OZavi (100)	1.17	1.47	0.87	1.11	*0.81*	*1.40*	*0.70*	*0.83*
OZavi (500)	4.83	5.51	0.87	1.11	*3.11*	*4.89*	*0.66*	*0.79*
OZrtr (100)	2.03	2.59	0.81	1.04	*1.60*	*2.05*	*0.86*	*1.02*
OZrtr (500)	8.57	8.32	1.03	1.31	*6.12*	*6.70*	*0.92*	*1.09*
OZshi (100)	1.92	2.79	0.73	0.93	*1.90*	*2.27*	*0.84*	*1.00*
OZshi (500)	8.79	8.48	1.06	1.36	*6.81*	*6.91*	*1.00*	*1.19*
OZall (100)	4.67	5.54	0.87	1.11	*3.53*	*4.58*	*0.82*	*0.97*
OZall (50)	2.52	3.10	0.85	1.09	-	-	-	-
	[K]	[Wm^{-2}]	[K/Wm^{-2}]		*[K]*	*[Wm^{-2}]*	*[K/Wm^{-2}]*	

Table 2: Radiative forcing, climate sensitivity, and efficacy according to the regression definition for the scaled ozone perturbations from aviation (avi), road traffic (rtr), and shipping (shi), calculated with the ECHAM and *UM (marked by italics)* climate models. The surface temperature response (2nd and 6th column) is the true equilibrium climate response and not derived through regression of the spin-up phase of a simulation (see text).

3.3 *Nonlinearities in the forcing-response relationship*

The unexpected and conceptually inconsistent variation of climate sensitivity and efficacy among patterns of the same structure but different scaling has been further explored for the ECHAM model for which this behaviour is most distinct. First, the number of simulations was enhanced to allow a more systematic investigation. Second, we determined the cloud radiative feedback as a likely candidate for the physical origin of the efficacy variations. Analysis confirms this hypothesis (Table 3).

	ΔT_{surf}	RF_{adj}	λ_{adj}	ΔCRF	$\Delta CRF/\Delta T_{surf}$
CO_2 (1 W/m^2)	0.703	1.010	0.696	−0.127	−0.181
CO_2 (doubling)	2.748	3.792	0.724	−0.340	−0.124
CO_2 (tripling)	4.572	6.160	0.742	−0.355	−0.078
OZavi (50)	0.617	0.862	0.716	−0.082	−0.082
OZavi (100)	1.167	1.593	0.733	−0.196	−0.168
OZavi (200)	2.201	2.849	0.773	−0.110	−0.050
OZavi (500)	4.832	5.730	0.843	+0.562	+0.116
OZrtr (100)	2.032	2.646	0.768	−0.034	−0.017
OZrtr (150)	2.900	3.689	0.786	+0.129	+0.044
OZrtr (500)	8.586	9.051	0.949	+3.262	+0.380
OZshi (100)	1.925	2.679	0.719	−0.018	−0.009
OZshi (150)	2.833	3.743	0.757	+0.155	+0.055
OZshi (500)	8.793	9.261	0.949	+3.888	+0.442
OZall (50)	2.524	3.279	0.770	+0.062	+0.025
OZall (100)	4.673	5.637	0.829	+0.774	+0.165
	[K]	[Wm^{-2}]	[K/Wm^{-2}]	[Wm^{-2}]	[Wm^{-2}/K]

Table 3: Equilibrium temperature response, radiative forcing, climate sensitivity, and cloud radiative feedback for ECHAM simulations forced by CO_2 and ozone perturbations (from aviation (avi), road traffic (rtr), and shipping (shi)) with different scaling. Radiative forcing and climate sensitivity are calculated using the IPCC definition (see text). The cloud radiative feedback (ΔCRF) is the equilibrium change of cloud radiative forcing, relative to the reference run.

For all ozone perturbations, increasing scaling induces a gradual change from negative cloud radiative feedback for moderate scaling to ever stronger positive feedback for heavy scaling. This shift to a qualitatively different cloud feedback regime causes higher climate sensitivity in the simulations with heavy scaling of the original perturbation. It is also evident that the shift occurs earlier for shipping than for aviation ozone, suggesting a crucial influence of static stability changes in the lower troposphere and respective consequences for low level clouds. It is notable that the effect of a changing cloud feedback regime is also present, but much less distinct, in case of an increasing CO_2 forcing. Here, the cloud radiative feedback remains negative up to a forcing level of 6 W/m^2, though the specific cloud feedback per unit temperature response (last column in Table 3) slightly decreases. As a consequence, the climate sensitivity increase with an increasing CO_2 forcing remains comparatively moderate and consistent with what is reported by Hansen et al. (2005).

4 NON-LINEAR FIT FOR CLIMATE SENSITIVITY AND EFFICACY

The dependence of the cloud radiative feedback on strength and pattern of the forcing offers a physical explanation for the unexpected increase of climate sensitivity and efficacy with increasing forcing. Assuming the existence of terms of higher order (in RF) in Eq. (1), and requiring that λ approaches a constant value for small radiative forcing, implies that to describe the correlation of climate sensitivity and radiative forcing a parabolic fit (Figure 1) is to be preferred above a linear fit:

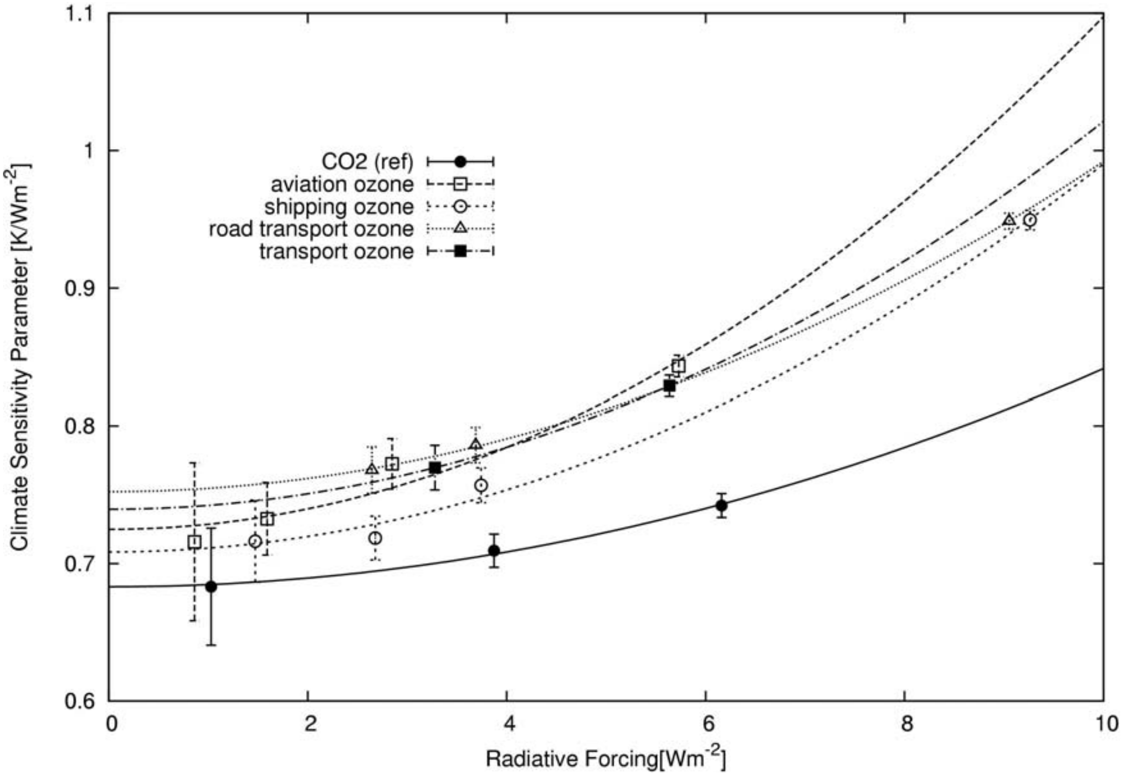

Figure 1: Dependence of the climate sensitivity parameter from the radiative forcing in the series of ECHAM simulations listed in Table 3. The symbols represent the individual simulations for CO2, individual transport sector ozone, and combined transport ozone, respectively. The curves indicate quadratic fits to the individual simulation series. A linear fit is not adopted, in order to ensure that the curves approach horizontal lines as RF approaches zero. The uncertainty bars indicate the 95% confidence interval for the simulated climate sensitivities (which is growing wider as ΔT_{surf} and λ decrease).

By taking the interception of the fitted curves with the ordinate we approximate unique values of the climate sensitivity parameter (λ_{adj}, in this case) for the original (small) perturbations. We apply this definition for all forcings (incl. CO_2), thus diverging from Hansen et al. (2005) who deliberately calculate the efficacy with respect to CO_2 doubling. If we define the efficacy values as explained, all transport ozone efficacies exceed unity and deviate by less than 10%. This means a much smaller excess over unity than found in earlier work (e.g., Stuber et al., 2005), probably because the perturbation patterns used here are smoother compared to the idealized patterns used in previous studies.

	λ_{adj}	r_{adj}
CO_2	0.692	1
OZavi	0.725	1.048
OZrtr	0.752	1.088
OZshi	0.707	1.021
OZall	0.739	1.068
OZall (approx)	0.729	1.053
	$[K/Wm^{-2}]$	

Table 4: Climate sensitivity and efficacy parameters derived from the parabolic fit of the results from the ECHAM simulations with individual transport related ozone perturbation patterns. The last line includes values of the same parameters derived for transport ozone by linear combination of the RF weighted values from the individual sector contributions.

Table 4 summarizes the respective values for λ_{adj} and r_{adj} reached in this way. It is suggested that, qualitatively, the ozone change pattern from road traffic has the largest efficacy while shipping ozone has the lowest efficacy close to unity. Using equation (5) to calculate a combined efficacy for a simultaneous forcing involving all transport sectors (OZall(approx)) yields satisfactory agreement with the fitted efficacy from dedicated runs with the same combination of forcings (OZall).

5 CONCLUSIONS AND OUTLOOK

Results from two series of equilibrium climate change simulations with respect to ozone perturbations caused by emissions by the transport sector confirm earlier findings suggesting the existence of efficacies significantly deviating from unity for this kind of non-homogeneous radiative forcing. Differences from the reference case (homogeneous CO_2 increase) are, however, not as large as found in previous studies which used idealized perturbation patterns. Individual ozone patterns clearly tend to show up distinctive efficacy values but inter-model differences render quantitative conclusions only indicative. A strong dependence of the climate sensitivity on the strength of a radiative forcing has become obvious from the simulations analysed for this study; this has required an extra effort to quantify well-defined efficacy value for some of the perturbation patterns.

In view of the difficulties in determining method-independent efficacy values, the relatively small deviation of the efficacies of transport related ozone perturbations from unity (not larger than 10 %), and occasional qualitative contradictions between the results of the two participating climate models, care is required when introducing the efficacy values from our simulations in assessment studies (e.g., Fuglestvedt et al., 2008). They may be used to test how sensitive a comparison of transport sector climate impacts depends on including distinctive efficacies. A more comprehensive understanding, validation of key feedbacks, and a consensus between different climate models will be necessary, however, before we can claim for sure that climate impact assessments are improved by the use of distinctive efficacies.

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