Climate sensitivity of radiative impacts from transport systems

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ABSTRACT: Comparing individual components of a total climate impact is traditionally done in terms of radiative forcing. However, the climate impact of transport systems includes contributions that are likely to imply climate sensitivity parameters distinctly different from the "reference value" for a homogeneous CO_2 perturbation. We propose to introduce efficacy factors for each component into the assessment. The way of proceeding is illustrated using aviation as an example, and prospects for evaluating the other transport system in the EU project QUANTIFY are given.

1 INTRODUCTION

The traditional way to compare the global climate impact of individual emission sectors, as well as specific contributions forming the total effect of some emission sector, is the radiative forcing (RF, Shine et al., 1990). RF is easily calculated by means of radiative transfer models and provides meaningful results even for very small perturbations that are unable to force statistically significant response signals in three-dimensional climate models. RF is also less model-dependent than other metrics of climate change (like the response of surface temperature, precipitation, storminess etc.), because the complex (in part poorly understood) feedbacks within the climate system (cp., Bony et al., 2006) do not enter the radiative transfer calculations. Such practical advantages make RF (and its derivatives like, e.g., the global warming potential, GWP) a seemingly ideal metric for assessment purposes. Consequently, RF and GWP have formed the basis of established emission trading systems.

As research on the climate impact of distinctly non-homogeneous forcing agents (like aerosols, ozone, or clouds induced by aircraft or ships) has received mounting interest, doubts have increased concerning the adequacy of RF for intercomparing relative impacts (e.g., Hansen et al., 1997, 2005; Cook and Highwood, 2003; Joshi et al., 2003; Stuber et al., 2005; Ponater et al., 2005). Here, we will discuss the concept of the EU project QUANTIFY to assess the climate impact contributions from transport systems in the light of current caveats in using RF as a respective metric.

2 CLIMATE SENSITIVITY

The idea to use RF as a metric for the climate change to be expected from some forcing origins from a recurrent empirical finding in climate modelling. Such experience has suggested a linear relation,

$$\Delta T_{surf} = \lambda \cdot RF \,, \qquad (1)$$

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between the global mean surface temperature response, ΔT_{surf}, and global mean radiative forcing, *RF*. The relating climate sensitivity parameter, λ, can be, with reasonable reliability, assumed to be independent of the nature of the forcing agent, i.e., its magnitude, longwave to shortwave spectral distribution, spatial structure, or seasonal variation. While λ is known to vary between different climate models, mainly due to a considerable model dependency of cloud feedbacks (Cess et al., 1989, 1996), many simulations implying changes of CO_2 concentration, other well-mixed greenhouse gases, or of the solar constant have confirmed the basic assumption within one and the same model configuration. Consequently, once the value of λ has been determined for the CO_2 case, it is then considered as a model constant applicable to all other agents. However, evidence is growing (see papers mentioned in the introduction) that this approach may fail on several occasions.

Table 1: Equilibrium climate sensitivity parameters (λ) as determined from ECHAM4 simulations. Global changes of CH_4, solar constant, CO_2, and ozone in the middle troposphere (MT), upper troposphere (UT), and lower stratosphere (LS) have been used as horizontally homogeneous forcing perturbations. The latter four agents have also been applied as a forcing restricted to the northern hemisphere extratropics (last two columns). See Stuber et al. (2005), for more details.

Agent	RF (Wm^{-2})	λ (K/Wm^{-2})	RF (Wm^{-2})	λ (K/Wm^{-2})
	Global perturbation		NH extratropics perturbation	
CO_2	1.0	0.81	1.0	1.12
Solar	1.0	0.82		
CH_4	1.0	0.88		
O_3(MT)	1.0	0.92	1.0	1.10
O_3(UT)	1.0	0.58	1.0	0.87
O_3(LS)	1.0	1.46	1.0	1.83

Table 1 gives an overview over equilibrium climate change simulations that have been conducted with the ECHAM4/T30.L19 climate model coupled to a mixed layer ocean module. The climate sensitivity parameter has been determined for a number of radiative perturbations, all normalised to a global mean of *RF*=1 W/m^2. While the conventional perturbations behave more or less in line with the assumption of constant climate sensitivity, there is a clear tendency to higher sensitivity for perturbation impacting on the northern hemisphere extratropics (Joshi et al., 2003). Compared to the reference value for CO_2, ozone has a distinctly higher sensitivity if the change occurs in the lower stratosphere, whereas the sensitivity is smaller for changes in the upper troposphere (Stuber et al., 2005). It is evident that non-homogeneous forcings may trigger specific feedbacks that are either less distinguished or less variable in the case of homogeneous forcings.

If the experience from non-homogeneous ozone perturbations already poses a challenge for the concept of constant climate sensitivity, simulations for non-homogeneous aerosol perturbations produce most embarrassing results: Table 2 recalls climate sensitivity experiments conducted by Cook and Highwood (2003) with the UREAD climate model of intermediate complexity. Forcing agents were scattering and absorbing aerosols in the lower troposphere (LT), the varied parameter was the aerosol single scattering albedo, ω.

Table 2: Climate sensitivity results from the UREAD climate model. Global horizontally homogeneous aerosol distribution, with fixed optical depth and asymmetry factor but varying single scattering albedo (ω) have been used as the forcing agent (see Cook and Highwood, 2003, for details).

Agent	ΔT_{surf} (K)	RF (Wm^{-2})	λ (K/Wm^{-2})
CO_2	1.9	3.81	0.50
Aero (LT), ω=1	-1.70	-4.72	0.36
Aero (LT), ω=0.95	-0.60	-3.02	0.20
Aero (LT), ω=0.9	0.60	-1.40	-0.43
Aero (LT), ω=0.85	1.80	0.14	12.86
Aero (LT), ω=0.8	2.90	1.61	1.80

Scattering aerosols (ω=1) cause negative RF and a surface cooling, yielding a climate sensitivity parameter smaller but still in the vicinity of the reference value for CO_2. As the absorbing character of the aerosol increases the λ values get more anomalous, culminating at negative λ for a critical single scattering albedo around ω=0.9, for which negative RF even causes a rise of global surface temperature. As pointed out by Cook and Highwood (2003) the reason for the irregular sensitivity in this case is the feedback on lower troposphere cloud cover (the "semi-direct aerosol effect"), which markedly decreases as a result of absorption heating. Due to some observational evidence indicating distinguished impacts of lower tropospheric aerosols on the hydrological cycle (e.g., Ramanathan et al., 2005), the semi-direct effect is not likely to be a mere model feature.

Summarising, climate model simulations with idealised non-homogeneous forcing agents suggest deviations from the reference climate sensitivity that are too strong to be ignored if, for example, ozone, aerosol, and CO_2 contributions to a total effect are to be compared. A way to account this for is the inclusion of efficacy factors (Hansen et al., 2005) in equation (1), writing instead

$$\Delta T^{(i)}{}_{surf} = r_i \cdot \lambda_{CO2} \cdot RF^{(i)} \qquad (2)$$

where $r_i=\lambda_i/\lambda_{CO2}$ would introduce the knowledge on an anomalous climate sensitivity λ_i for the component contributing the forcing $RF^{(i)}$. Quantifying individual components in terms of $\Delta T^{(i)}{}_{surf}$ rather than $RF^{(i)}$ may be expected to provide a fairer, more reliable, assessment. Introducing efficacy factors in this way is encouraged by the finding that the model dependence of those factors seems to be smaller than the model dependence of the climate sensitivity parameter itself (Hansen et al., 1997; Joshi et al., 2003). Another favourable point to mention is the possibility to include efficacies into the calculation of GWPs (Fuglestvedt et al., 2003; Berntsen et al., 2005) or into other linear extensions of the radiative forcing concept (e.g., Ponater et al., 2006).

3 EFFICACY OF AIRCRAFT CLIMATE IMPACT COMPONENTS – A TEST CASE

Compared to other transport sectors knowledge on the climate impact from aircraft is relatively far advanced. RF values for the various contributions were first quantified for an IPCC special report (Penner et al. 1999) and improved by subsequent research work. However, aviation effects beyond CO_2 and CH_4 just exhibit the properties that make anomalous climate sensitivity likely to occur: They are non-homogeneous in time and space (both horizontally and vertically). We have performed a series of equilibrium climate change simulations with the ECHAM4/T30.L39(DLR) climate model, in order to determine climate sensitivity parameters separately for each impact component (Ponater et al., 2005; 2006). It is important to note that the calculation of a statistically significant surface temperature response (ΔT_{surf}) requires, in most cases, a scaling of the forcing perturbation, as the unscaled RFs generally range well below 0.1 Wm^{-2} for present day conditions (Penner et al., 1999; Sausen et al., 2005). The results for the individual climate sensitivity and efficacy values are shown in Table 3:

Table 3: Results (global annual averages) from aircraft climate sensitivity simulations. CO_2 and CH_4 perturbations were normalised to 1 Wm^{-2}. Two aircraft O_3 perturbations of the Grewe et al. (2002, their Fig. 3) type (i.e., for year 2015) were used in two separate simulations. The perturbations for contrails and for H_2O were artificially scaled by factors between 50 and 80, relative to actual present day conditions. See Ponater et al. (2005, 2006) for more details.

	CO_2	CH_4	$O_3(1)$	$O_3(2)$	H_2O	contrails
RF (Wm^{-2})	1.00	1.00	0.059	0.062	0.06	0.19
ΔT_{surf}(K)	0.74	0.86	0.060	0.071	0.05	0.08
λ (K/ Wm^{-2})	0.74	0.86	1.02	1.15	0.83	0.43
r	1	1.18	1.37	1.55	1.14	0.59

As expected some *r* values differ significantly from unity. Aircraft ozone changes have a by 40 % higher efficacy, while the climate sensitivity of contrails is considerably lower than the reference value. Figure 1 shows the corresponding zonal mean RFs, and zonal mean cross sections of the atmospheric temperature response. Note the specific characteristics of aircraft ozone, water vapour, and contrail perturbations with respect to the latitudinal profile and the combination of longwave and shortwave radiative components. Moreover, contrail RF is extremely variable on short time scales, and ozone RF includes strong seasonal variability. While we emphasise that equations (1) and (2) may be applied only for global and annual means, the three-dimensional climate simulations basic to the averaged values of Table 3 offer ample opportunity to investigate local forcings and feedbacks and to discuss their relevance for the global response in each case (e.g., Stuber et al., 2005; Ponater et al., 2005). Still, the current level of process understanding needs to be advanced and available knowledge on, e.g., model dependency issues is very sparse. In particular, important aspects of the interaction between aerosols, clouds and radiation are little explored. Even the sign of the indirect impact of aircraft emitted soot on climate is currently unknown (Hendricks et al., 2005).

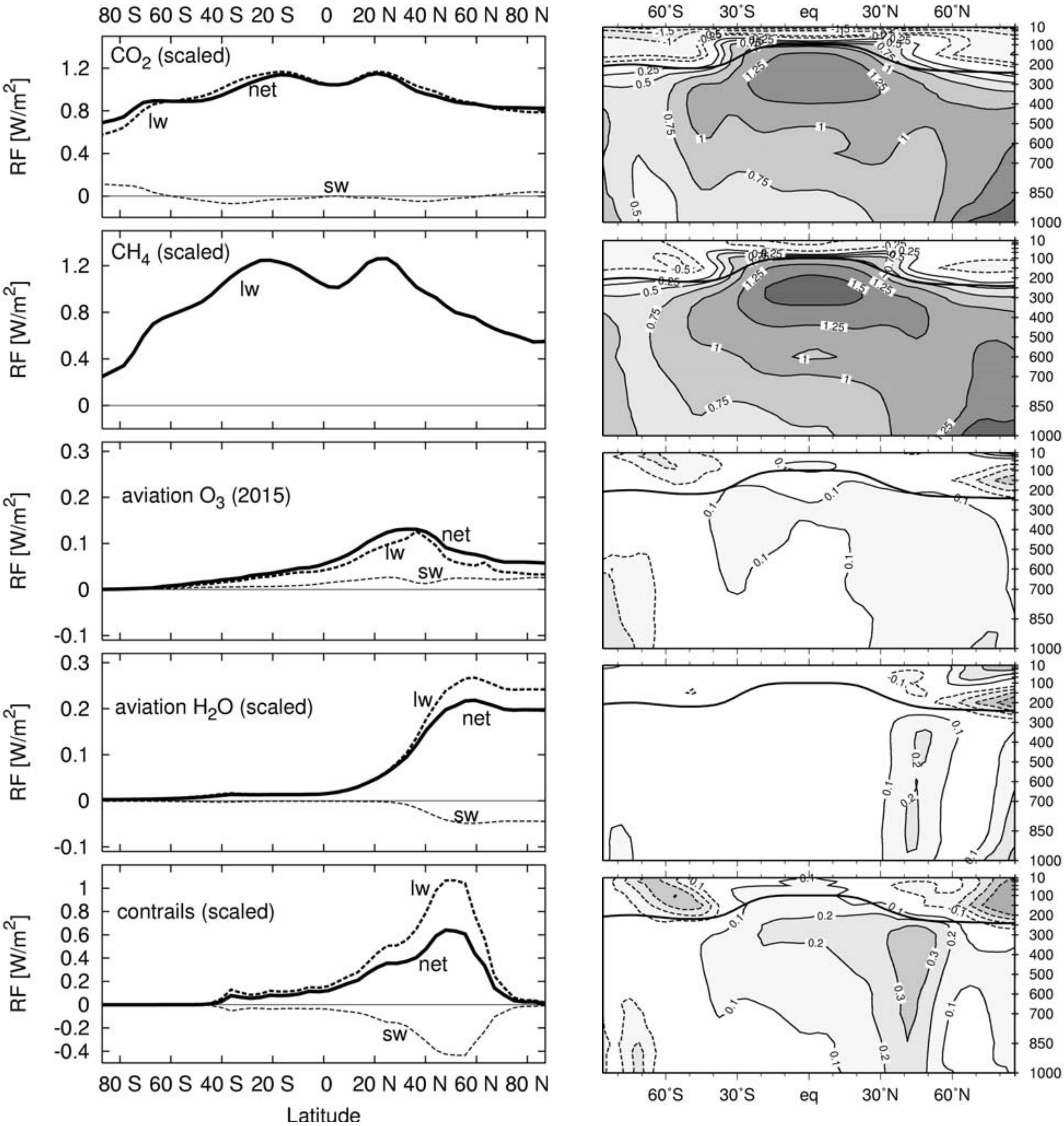

Figure 1: Zonal mean radiative forcing profile (Wm^{-2}, left) and zonal mean temperature reponse (in K, right) caused by various aircraft impact components as simulated with the ECHAM4 GCM. Note that the actual aircraft induced perturbations had to be scaled (see Table 3, and main text). Annual averages of forcing and response are shown. The essential part of the temperature response is statistically significant.

4 EFFICACY OF TRANSPORT CLIMATE COMPONENTS

The generalisation of the efficacy concept outlined in Section 2 to all transport related emissions, as it is intended in the QUANTIFY project, will add further complexity. First, aerosol induced forcings and feedbacks form a main part of the total effect for surface sources (this is particularly true for ships), and it is largely unknown how the aerosol-cloud interaction effects discussed in the context of Table 2 will manifest globally, if the perturbations are restricted to certain geographical regions. This subject will be one of the central issues in QUANTIFY. Second, for both aerosols and ozone the individual spatial structure of the perturbation is likely to create an individual efficacy value. Figure 2 illustrates how different, e.g., the ozone change patterns of the different sectors of transport can be expected to be, and in view of the results shown in Table 1 this is almost certain to modify the climate sensitivity. However, if the approach we follow is to make sense, the climate sensitivity must remain well-defined, in reasonable limits, for each contributing perturbation.

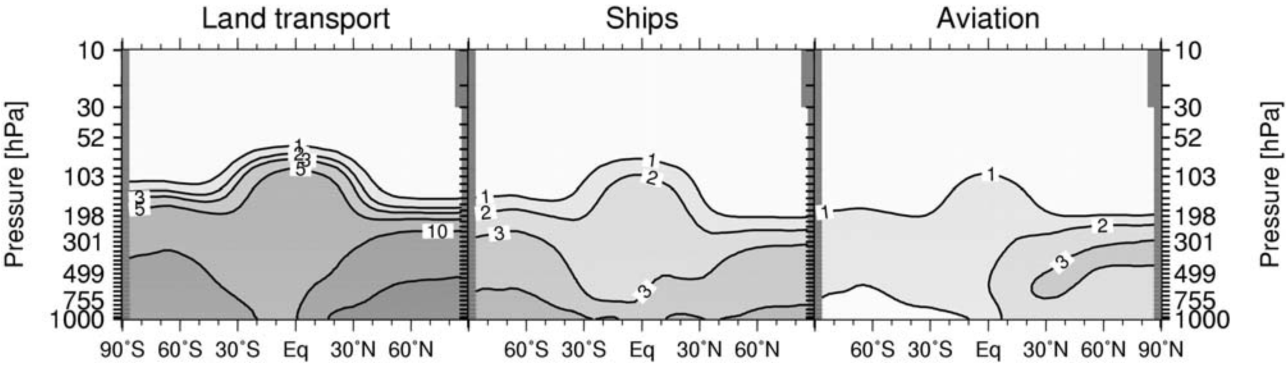

Figure 2: Annual mean ozone change induced by NO_x emissions from road transport, ship transport, and aviation, for typical 1990ies conditions. Values indicate fraction of the total ozone concentration (in %). Results are extracted from the interactive chemistry-climate model simulation discussed by Dameris et al. (2005) Contributions from individual NO_x sources were separated according to the Grewe (2004) method. Contour lines are 1, 2, 3, 5, 10, 20 %.

This requires, above all, a high degree of linearity for each contribution, i.e., the efficacy values in equation (2) must not depend significantly on the magnitude of RF. Otherwise any scaling, as has been done for the aviation perturbations discussed in Section 3, is prohibited and our concept would be bound to fail. Therefore, extra linearity checks are intended in QUANTIFY. Third, if distinctive efficacy values can indeed be determined for each contribution it will be necessary to identify the degree of additivity, if the components are recombined to yield an efficacy for the total effect (either for each single transport sector, or for the gross effect of total transport). Respective non-linearities have been reported, e.g. for the overall interaction of greenhouse gas and aerosol forcing (Feichter et al., 2004). If such evidence consolidates, a sufficient understanding must be developed in order to arrive at a reasonable synthesis of the separate forcing, efficacy, and response results, and in order to eventually convert our knowledge of climate interaction processes to assessment numbers that are reliable enough to be translated into damage functions or other measures of socio-economic impact (see contribution by Shine, this volume).

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Results from pulse scenario experiments with the CNRM-CM3 global coupled model

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ABSTRACT: In order to validate Simple Climate Models (SCMs), the response of the Atmosphere Ocean General Circulation Model (AOGCM) CNRM-CM3 to specific forcing scenarios is studied. Upon pre-industrial background conditions, a sudden perturbation in the solar constant or the CO_2 concentration was applied, followed by an exponential decay of the perturbation. Identical experiments performed with SCMs allow than a validation of the SCMs parameters.

The CNRM-CM3 model is a global coupled climate model which consists of an atmosphere general circulation model, an ocean general circulation model, and a sea ice model. In addition to the validation of SCMs, these experiments can also be used to better understand the characteristics of AOGCMs. The atmosphere and ocean show clearly distinct response times to the forcings. Where the response time for the atmosphere is between 5 and 10 year, the response time for the ocean varies between 60 and 120 year. Furthermore, the influence of the initial conditions is not very large and the response time of the ocean is not very robust with respect to the length of the perturbation.

Comparison with results from earlier simulations with the CNRM-CM3 model where the CO_2 concentration was increased in a gradual way show that, although the forcing scenarios used in these new simulations are strongly transient, they can give valuable information about the characteristics of the model.

1 INTRODUCTION

AOGCMs are the most accurate models to study the effect of different emission scenarios on the Earths climate. However, these models are too computationally expensive to be used for large sets of emission scenarios. Simple Climate Models (SCMs) which are computationally less expensive (and therefore also less accurate) can be used to study the impact of a large set of emission scenarios. Such models therefore allow to study the impact of separate transport sectors and to make sensitivity studies.

In a first step, the SCMs should be validated. Performing a limited set of dedicated experiments as well with the SCMs as with the AOGCMs could allow an interesting comparison between the behaviour of the SCMs and the AOGCMs. Two types of experiments which have a quite different impact on the atmosphere are chosen: changing the solar constant and changing the CO_2 concentration. Changing the solar constant affects the short-wave radiation and is felt mostly at the Earths surface; changing the CO_2 concentration affects the thermal infrared radiation and is initially felt mostly in the middle of the troposphere. The AOGCM experiments are performed with the Unified Model (UM) by the University of Reading, and with the CNRM-CM3 model by the CNRM. In a second step, the SCMs can be used to run a large set of climate simulations.

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