Quantifying the effects of aviation on radiative forcing and temperature with a climate response model

L. Lim*, D.S. Lee,
Dalton Research Institute, Department of Environmental & Geographical Sciences, Manchester Metropolitan University, UK

R. Sausen, M. Ponater
Space and Atmospheric Research Group, Imperial College London, UK

Keywords: Climate response, aviation, efficacy

ABSTRACT: Simplified climate models can be used to calculate and to compare temperature response contributions from small forcings without the need for considerable computer resources. A linear climate response model using Green's functions has been formulated to calculate radiative forcing (RF) and the global mean temperature response from aviation. The model, LinClim, can calculate aviation RF for CO_2, O_3, CH_4, water vapour, contrails, sulphate and black carbon aerosols. From these RFs, temperature responses may be calculated for individual effects in order to determine their relative importance by applying preliminary values for efficacies. The LinClim model is tuned to reproduce the dominant mode of its parent coupled atmosphere-ocean GCM, ECHAM4/OPYC3. LinClim is able to reproduce the IPCC (1999) 2050 aviation-related forcings. The model is shown through some example application analyses to be a useful tool for exploring the effects of aviation on RF and temperature response.

1 INTRODUCTION

Aircraft emissions may influence climate from a number of emissions and effects. These effects have been reviewed and assessed in the Intergovernmental Panel on Climate Change (IPCC) Special Report '*Aviation and the Global Atmosphere*' (IPCC, 1999). More recently, Sausen et al., (2005) gave an update to the IPCC results on the aviation's impact on climate by means of the metric 'radiative forcing of climate'. This metric has been adopted by the IPCC (IPCC, 1990) and the scientific community to assess different anthropogenic effects on climate. The RF concept has proven useful as there is an approximately linear relationship between the global mean radiative forcing (*RF*) and the associated equilibrium global mean surface temperature change (ΔT_s), i.e.:

$$\Delta T_s \approx \lambda\, RF \ , \qquad (1)$$

where λ is the climate sensitivity parameter (unit K/Wm^{-2}). For many years λ has been considered being a model constant, independent of the type of forcing. More recently, in a number of studies, it has been shown that λ is to some extent also dependent on the type of perturbation, in particular for non-homogeneously distributed climate change agents, e.g., aircraft-induced O_3 perturbations (Hansen et al., 1997; Forster and Shine, 1997; Ponater et al., 1999; Joshi et al., 2003). This is sometimes denoted the 'efficacy' (Hansen et al., 2005) and is defined as:

$$r_i = \lambda_i / \lambda_{CO2} \ , \qquad (2)$$

where λ_i and λ_{CO2} are the climate sensitivity parameters associated with perturbations of the climate change agent *i* and of CO_2, respectively. Considering also the efficacy, eq. (1) modifies to

$$\Delta T_s \approx r_i \lambda_{CO2} RF \ . \qquad (3)$$

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[*] *Corresponding author:* Ling Lim, Dalton Research Institute-CATE, Manchester Metropolitan University, Faculty of Science and Engineering, John Dalton East Building, Chester St, Manchester M1 5GD, UK. Email: l.lim@mmu.ac.uk

The ideal way to explore climate scenarios would be to perform simulations with general circulation models (GCMs). However, GCMs are very complex and computationally demanding: a scenario may need to be run (depending on the climate perturbation) for decades of simulation time taking processing time in the order of weeks to months on a high performance computer (in particular if chemistry is included). The necessity for long simulation periods arises from climate inertia effects and the requirement to separate signal from noise. For aircraft perturbations that are relatively small, this is a particularly difficult problem. In order to overcome the high computational costs associated with determining environmental responses with GCMs, simplified climate response models may be used. Such models are generally tuned or parameterized to reproduce the main characteristic responses of GCMs (such as the temporal evolution of the global mean near surface temperature) and have been used extensively by the IPCC to explore the impacts of a large range of climate scenarios (IPCC, 2001).

Sausen and Schumann (2000) (hereafter referred to as S&S 2000) demonstrated that some of the global mean environmental responses to particular engine technology development scenarios could be conveniently explored with a simple linear climate response model that was computationally efficient. This model went beyond RFs to compute temperature responses over various timescales. Using temperature response rather than RF allows an examination of the effects of r_i by looking at the time-development of changes in ΔT_s, and an assessment of the relative merits of abatement technologies in terms of climate protection.

In this paper, a simplified climate response model, LinClim, which builds upon the approach of S&S (2000) is presented. The scope of the model has been expanded to include the full suite of aviation-specific effects identified by the IPCC (1999). These include RFs and temperature response formulations for CO_2, formation of O_3 and CH_4 destruction due to NO_x, water vapour, contrails, sulphate, soot and indirect clouds.

2 MODEL DESCRIPTION

The modelling approach adopted was to calculate the emissions and subsequent concentrations of a climate gas, calculate its RF, and then to calculate the ΔT_s due to the RF using a simplified climate response function. LinClim includes formulations which are consistent with either the IPCC (1999) or TRADEOFF (Sausen et al., 2005) data (denoted '*99*' and '*TO*', respectively). For methodologies that involves reference year scaling, the values may be obtained from various sources.

2.1 *Carbon dioxide (CO_2)*

In order to calculate the full CO_2 contribution to RF and temperature response, historical fuel and extrapolation out to 2100 were calculated using S&S (2000) methodology. Emissions of CO_2 are then calculated using carbon mass fraction of 0.86 for aviation fuel (S&S 2000). The response of CO_2 concentrations to an emissions rate is modelled using Hasselmann et al., (1997), which approximates to the results of the carbon cycle model of Maier-Reimer and Hasselmann (1987).

The RF of a CO_2 increase is dependent upon the reference concentration because of spectral saturation, such that in calculating the impacts of CO_2 from aviation, it is necessary to know the 'background' RF. Historical CO_2 concentration data from 1800 until 1995, and thereafter until 2100 from IPCC scenario IS92a (all natural and anthropogenic sources including aircraft emissions) were used as background (S&S 2000). The contribution of aviation CO_2 concentrations are calculated explicitly, the concentration being assumed to be the difference between background and aviation concentrations. The RF of CO_2 may then be calculated using the simplified expression adopted by IPCC (1997) or IPCC (2001).

2.2 *NO_x-induced ozone (O_3) and methane (CH_4)*

The aviation O_3 and CH_4 RF methodology assumes that there is a linear relationship between aviation NO_x emissions and O_3 (and indirect CH_4) RF changes (IPCC, 1999), i.e.:

$$RF_{O3,CH4}(t) = RF_{O3,CH4}(ref\ year) \times \frac{E_a(t)}{E_a(ref\ year)} \times \frac{EI_{NOx}(t)}{EI_{NOx}(ref\ year)}\ , \qquad (4)$$

where E_a is the aircraft fuel burnt per year, and EI_{NOx} is the emissions index of nitrogen oxides per mass of fuel burnt.

2.3 *Water vapour (H_2O)*

Similar to the calculation of aviation induced O_3 and CH_4, a simplified linear approach is taken for water vapour where the RF scales linearly with fuel use, i.e.:

$$RF_{H2O}(t) = RF_{H2O}(ref\ year) \times \frac{E_a(t)}{E_a(ref\ year)} , \tag{5}$$

2.4 *Line-shaped contrails*

Contrails RF is assumed to scale with fuel burn and an additional factor, *F*, to account for the evolution of fleet and flight routes over time (IPCC, 1999) and *F* was then derived by scaling this RF value to the published values in IPCC (1999) for the years 2015 and 2050. Post 2050, *F* is assumed to be constant. The *F* values are summarized in Table 1.

Table 1: Correction factor, *F* to account for fleet evolution and flight routes

Year	Technology 1	Technology 2
1992	1.00	1.00
2015	1.48	1.48
2050	1.70	1.64

2.5 *Sulphate (SO_4) and soot (BC) particles*

Aviation SO_4 particle emissions were derived from the sulphur content of fuel, as in eq. (6), where $E_{SO4}(t)$ is the aviation emissions at time *t* (Tg S), $EI_{Sulphur}$ is the emissions index 0.0004 kg S per kg fuel, β is the effective conversion factor from fuel-sulphur to optically active sulphate, following IPCC (1999), we adopt $\beta = 50\%$.

$$E_{SO4}(t) = \beta \times EI_{Sulphur} \times E_a(t) \tag{6}$$

Aviation soot (black carbon, BC) is calculated using eq. (7), where $E_{BC}(t)$ is the aviation emissions at time *t* (Tg BC) and EI_{BC} is the emissions index 0.00004 kg black carbon per kg fuel (IPCC, 1999).

$$E_{BC}(t) = EI_{BC} \times E_a(t) \tag{7}$$

RF for particles is scaled to the respective particle emissions and externally calculated RF.

$$RF_{SO4,BC}(t) = RF_{SO4,BC}(ref\ year) \times \frac{E_{SO4,BC}(t)}{E_{SO4,BC}(ref\ year)} \tag{8}$$

2.6 *Aviation-induced cirrus*

Similar to the water vapour RF calculation, it is assumed that RF of aviation-induced cirrus scales with fuel usage. However, due to the large uncertainties in aviation-induced cirrus calculation (c.f., Sausen et al., 2005; or Mannstein and Schumann, 2007), we refrain from including the contribution from this effect in the final results.

2.7 *Temperature response*

The temperature response approach was devised by Hasselmann et al., (1993) and has been widely used thereafter (e.g., Hasselmann et al., 1997; S&S 2000). The formulation presented by S&S (2000) has been rearranged to include the perturbation's efficacy:

$$\Delta T_i(t) = r_i \lambda_{CO2} \int_{t_0}^{t} \hat{G}_T(t-t') RF_i(t') dt' , \tag{9}$$

$$\hat{G}_T(t) = \frac{1}{\tau} e^{-t/\tau} , \tag{10}$$

where ΔT_i is the temperature response (K) due to perturbation i. r_i is the associated efficacy, λ_{CO2} is the CO_2 climate sensitivity parameter (K/Wm^{-2}) of the parent GCM, RF_i is the associated radiative forcing (Wm^{-2}). The revised Green's function is $\hat{G}_T(t)$, τ is the lifetime (e-folding time) of a temperature perturbation (years). The current version of LinClim is tuned to reproduce the transient behaviour of the full-scale atmosphere ocean model ECHAM4/OPYC3 (Roeckner et al., 1999). The value of λ_{CO2} is 0.64 K/Wm^{-2} and τ is 37.4 years. The values for r_i are summarized in Table 2.

Table 2: Efficacies, r_i

Perturbation	Reference	r_i (range)
CO_2, SO_4, BC		1
Aviation O_3	Ponater et al., 2006	1.37 (1 – 2)
CH_4	Ponater et al., 2006	1.18 (1 – 1.2)
H_2O	Ponater et al., 2006	1.14
Contrails	Ponater et al., 2006	0.59

3 APPLICATION

The aviation RF results from LinClim using the '*99'* parameters (scaled to IPCC (1999) reference values parameters summarized in Table 3), denoted as LC-99, are presented in Table 4. The IPCC (1999) results are basically reproduced. The deviations in RF_{CO2} result from a slightly different CO_2 concentration. There were noticeable differences in the 1992 RF_{O3} and $RF_{Contrails}$. This is due to the difference in the 1992 fuel burnt in LinClim (165.1 Tg from S&S, 2000) and the IPCC (1999) (160.3 Tg). Small differences were yielded also for RF_{O3} and RF_{CH4} in future years. This is because the IPCC (1999) RF_{O3} and RF_{CH4} results were obtained from CTM runs, whereas the results from LC-99 were simply scaled to the NO_x emissions.

Table 3: Reference year (1992 and 2000) parameters used in the example applications

Parameter	Unit	Reference values in 1992 (used in LC-99)	Reference values in 2000 (used in LC-TO)
E_a	Tg/Yr	160.3*	169.0†
E_{SO4}	Tg S	0.032*	0.0338‡
E_{BC}	Tg BC	0.006*	0.0068‡
EI NO_x	g NO_2/kg fuel	12.0*	12.7†
RF_{O3}	W/m^2	0.023*	0.0219‡
RF_{CH4}	W/m^2	-0.014*	-0.0104‡
RF_{H2O}	W/m^2	0.0015*	0.0020‡
$RF_{Contrails}$	W/m^2	0.020*	0.0100‡
RF_{SO4}	W/m^2	-0.003*	-0.0035‡
RF_{BC}	W/m^2	0.003*	0.0025‡

*IPCC (1999), †Gauss et al. (2006), ‡Sausen et al. (2005).

A second set of parameters from the TRADEOFF study (Sausen et al., 2005) were used to form an updated version of LinClim, denoted as LC-TO (Table 3). These updated results (see Table 4) show that the contribution of aviation RF is lower than in the previous assessments, both for 1992 and for future scenarios.

Figure 1 shows the total aviation RF (without aviation-induced cirrus) and the associated temperature changes (with and without considering the efficacies) for scenario Fa1 calculated using LinClim with the TRADEOFF parameters (LC-TO). It is interesting to note the role of efficacies in the temperature prediction. Using an efficacy of 1 for all perturbations, the temperature response is approximately the same as the prediction including individual efficacy values for specific perturbation (as listed in Table 2). By chance, the larger contributions from O_3 and H_2O are offset by the smaller contribution from contrails and the more negative contribution from CH_4. However, by changing the efficacy of O_3 to the lower (r_{O3} = 1) and upper (r_{O3} = 2) bounds, the temperature response is 20% lower (r_{O3} = 1) or 33% higher (r_{O3} = 2) than the case where r_{O3} = 1.37 (as in Table 2) at 2100. This shows that the role of efficacies may become increasingly important in determining the tradeoffs between different engine technology options, in particular with respect to NO_x which causes component impacts of high efficacy.

Table 4: RF comparison of LinClim with the IPCC (1999) parameters (LC-99) and with the TRADEOFF parameters (LC-TO). (Cont. = Contrails)

	Data	CO_2	Radiative forcing (W/m2)							
Scenario	source	(ppmv)	CO_2	O_3	CH_4	H_2O	Cont.	SO_4	BC	Total
NASA-1992	IPCC	1.0	0.018	0.023	-0.014	0.002	0.020	-0.003	0.003	0.049
	LC-99	1.3	0.022	0.024	-0.014	0.002	0.021	-0.003	0.003	0.054
	LC-TO	1.3	0.019	0.020	-0.012	0.002	0.010	-0.003	0.002	0.038
NASA-2015	IPCC	2.5	0.038	0.040	-0.027	0.003	0.060	-0.006	0.006	0.114
	LC-99	2.8	0.044	0.052	-0.032	0.003	0.060	-0.006	0.006	0.128
	LC-TO	2.8	0.038	0.044	-0.025	0.004	0.028	-0.007	0.005	0.087
FESGa (tech1) 2050	IPCC	6.0	0.074	0.060	-0.045	0.004	0.100	-0.009	0.009	0.193
	LC-99	6.3	0.080	0.086	-0.052	0.004	0.100	-0.009	0.009	0.218
	LC-TO	6.3	0.068	0.073	-0.044	0.006	0.047	-0.010	0.007	0.147
FESGa (tech2) 2050	IPCC	6.1	0.075	0.047	-0.035	0.005	0.100	-0.009	0.009	0.192
	LC-99	6.4	0.081	0.066	-0.040	0.005	0.100	-0.009	0.009	0.212
	LC-TO	6.4	0.069	0.057	-0.027	0.006	0.047	-0.010	0.007	0.149

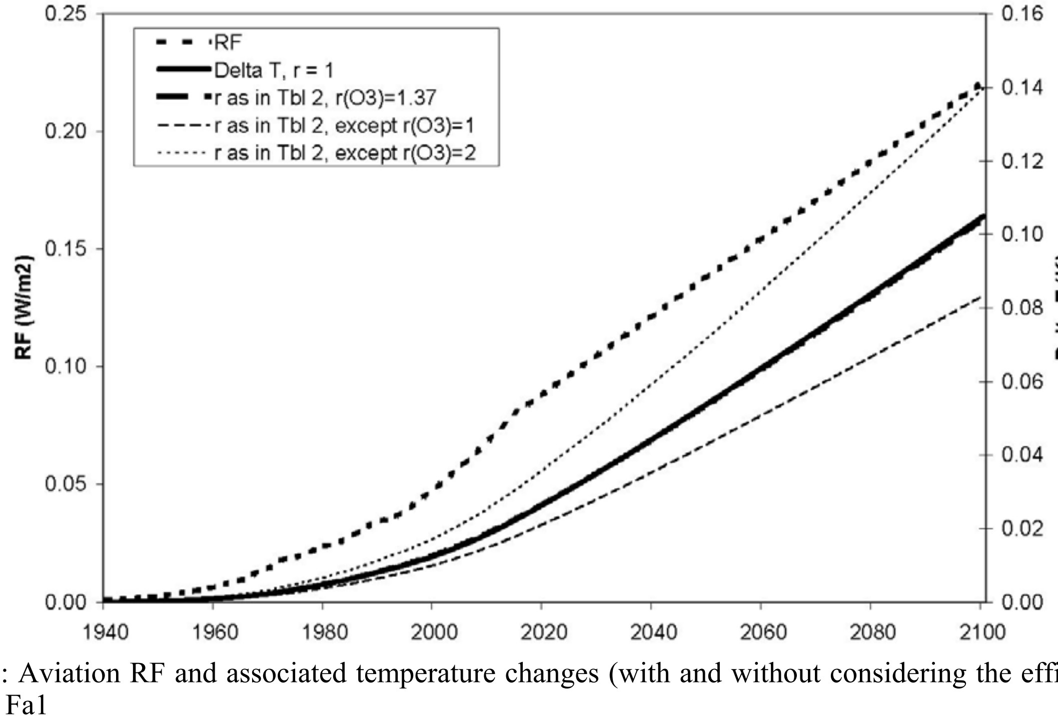

Figure 1: Aviation RF and associated temperature changes (with and without considering the efficacies) for scenario Fa1

4 CONCLUSIONS AND FURTHER WORK

The RF and temperature response results of the simple climate response model, LinClim, are presented. LinClim is able to predict the temperature response from the full suite of aviation perturbations. The present day and future scenario RF results compared well with the published IPCC (1999) values. LinClim's RF results are not intended to replace other RF estimates, but are rather used to describe the contribution of individual impact components to the total aviation effect for transient emission scenarios. In future work the model will be applied more extensively to various technology and growth scenarios to understand the role of aviation and by how technology improvements may be best targeted. Moreover, the model will also be useful in exploring more appropriate climate metrics than RF for policy applications.

5 ACKNOWLEDGEMENTS

This study was funded by the EU IP QUANTIFY and EU NoE ECATS. Further support was given from the UK Department of Trade and Industry (DTI) and the UK Department for Transport (DfT).

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