The Role of Aviation Emissions in Climate Stabilization Scenarios

David S. Lee[1], Ling L. Lim[1] and Sarah C. B. Raper[2]
[1] Manchester Metropolitan University, Dalton Research Institute
[2] University of East Anglia, School of Environmental Sciences

Abstract

Climate stabilization is embedded in UK and EU policy objectives and stabilization scenarios make assumptions over short and long-term emissions reductions. Air traffic, however, is increasing at 3 – 5% per year. The technological possibilities of reducing aircraft CO_2 are limited and projected traffic growth overwhelms gains from fuel efficiency. MAGICC and a climate response model are used to examine the addition of aviation effects (CO_2, O_3, CH_4, sulphate, soot and contrails) onto stabilization scenarios. Aviation makes a small but significant contribution to radiative forcing and global temperature responses. Whilst this is small globally, the necessary policy response of the three major centres of aviation (North America, Europe and the Far East) may be demanding; these emissions potentially form a large fraction of a country or region's CO_2 emissions. This may provoke further thinking over emissions trading as the way forward to incorporate international aviation emissions into Kyoto and post-Kyoto targets.

1 Introduction

The impacts of aviation on climate have been investigated for some time, with the focus being on radiative forcing (RF) from chemical and physical changes to the earth's atmosphere [1]. Aircraft emissions are thought to affect RF positively from CO_2, O_3, soot and contrails and negatively from sulphate and reductions in ambient CH_4. The aviation forcing in 1992 was estimated by the IPCC to be 0.05 W m^{-2} (3.5% of the total forcing), rising to 0.19 W m^{-2} in 2050 (5% of the total forcing), according to a central scenario [1]. More recent estimates of the RF from individual aviation effects and the total has been revised in the light of improved science but the total forcing remains of the same order for 2000 [2].

Whilst many studies have examined aviations effects on RF, few have examined the temperature response. This is because of the difficulties associated with calculating temperature responses from such small forcings in GCMs. In order to overcome both this difficulty, and that associated with long integrations demanding considerable computer resources, simplified climate models can be used as an initial assessment of scenarios, as has been done extensively for more general scenarios in the IPCC's Third Assessment Report [3]. The only study thus far of aviation's effects of RF on temperature has been to examine the CO_2 and NO_X effects [4]. No studies have examined the particular role of aviation in climate stabilization scenarios.

Here, an extended version of the model of Sausen and Schumann [4] is used along with the MAGICC model [5] to examine the effects of global aviation effects on climate stabilization scenarios. Climate stabilization scenarios are arrived at from an inverse modelling approach that calculates the emissions (and their rate of change) required to achieve stabilization of atmospheric CO_2 concentrations at different levels (e.g. 450, 500, 550 ppm). Such scenarios do not generally consider the individual contributions of particular sectors. In this study, we use an IPCC aviation emissions scenario for aviation (Fa1), extended to 2100 according to [4], and add these on to selected WRE scenarios [6].

2 Modelling methodology

The MAGICC model is a coupled gas-cycle/climate energy balance model and has been described in detail elsewhere [5, 7, 8]. MAGICC is used for calculations of background CO_2 concentrations and used as a 'reference' model for validating the climate response model used for aviation effects 'LinClim'.

The climate response model is based upon the original approach of Hasselmann *et al.*, 1993 [9] and was adapted by Sausen and Schumann [4] for calculating RF of aviation CO_2 and O_3 (from NO_x emissions) and their temperature responses. Sea-level rise from CO_2 is also calculated but not considered here. LinClim [10] has been formulated to calculate the forcings from the various aviation effects, which are detailed below. Since the climate sensitivity of some aviation effects are thought to differ from the climate sensitivity to CO_2 (λ), the model has been reformulated to account for species/effect specific values of λ as follows:

$$\Delta T(t) = r^* \lambda \int_{t_0}^{t} \hat{G}_T(t-t')RF(t')dt' \quad (1)$$

where:

$\Delta T(t)$	=	Global mean surface temperature response (K)
r^*	=	Species / effect-specific parameter = $\dfrac{\lambda_{species}}{\lambda_{CO_2}}$
λ	=	Climate sensitivity parameter (K/Wm^{-2})
$\hat{G}_T(t)$	=	$\dfrac{1}{\tau}e^{-t/\tau_T}$, τ is the coefficient of the impulse response function
$RF(t)$	=	RF (W/m^2)

Values of r^* were derived from simulations of various aviation forcings from ECHAM3 and ECHAM4 [10]. Emissions of aviation NO_X result in reductions in background concentrations of CH_4. Background CH_4 concentrations were derived from historical observations and modelled future emissions using a global mean mass balance from Wigley *et al.*, 2002 [11] that accounts for OH, soil and stratospheric sinks. The lifetime of CH_4 depends upon its own concentrations and those of OH and this was corrected using the approach of the IPCC [3], accounting for emissions of NO_X, CO and VOCs. The destruction of CH_4 from aviation NO_X emissions was taken from fractional reductions reported in [1] from CTM simulations. Lastly, CH_4 RF was calculated according to [3]. Thus the RFs from CH_4 and aviation reductions in CH_4 RF could be calculated.

Total tropospheric O_3 was calculated from the simplified methodology given in [3] using emissions of CH_4, NO_X, VOCs and CO and the RF calculated using the IPCC [3] methodology. Aviation RF from O_3 was calculated according to [4], assuming a linear relationship between forcing and NO_X emissions rate. Sulphate and soot RF was calculated by scaling the total particle concentration to the emissions for 2000 and scaling the RF to the RF for 2000 [3]. The aviation fraction was calculated from aviation fuel burn and an assumed S content of the fuel. Soot concentrations and RF were calculated similarly. Lastly, contrail RF was calculated in similar fashion to O_3, scaling linearly with fuel usage from a normalized forcing in a given year.

All temperature responses were calculated assuming a similar temperature response to that of CO_2, accounting for different values of r^*.

3 Model – model comparison

Before proceeding with usage of data and background concentrations from MAGICC, it was necessary to demonstrate that LinClim was producing reasonable results. Thus, comparisons of concentrations and RF were made between LinClim and MAGICC. In Table 1, data at 25 year intervals are provided for LinClim, MAGICC and data from the IPCC Third Assessment Report [3]. RF from CH_4, total tropospheric O_3 and total SO_4 are compared.

	CO_2			O_3			CH_4			SO_4		
	LC	M'C	TAR	LC	M'C	TAR	LC	M'C	TAR	LC	M'C	TAR
2000	0.23	0.23	0.28	0.06	0.02	0.06	0.02	0.02	0.02	0.00	0.01	0.00
2025	1.17	1.17	1.19	0.25	0.17	0.25	0.15	0.16	0.15	-0.15	-0.14	-0.16
2050	2.22	2.22	2.24	0.30	0.21	0.30	0.24	0.25	0.24	0.03	0.04	0.03
2075	3.09	3.09	3.15	0.26	0.17	0.28	0.19	0.20	0.19	0.21	0.21	0.21
2100	3.72	3.72	3.84	0.20	0.13	0.20	0.09	0.10	0.10	0.24	0.24	0.24

Table 1 Comparison of CO_2, O_3, CH_4 and SO_4 RFs from LinClim (LC), MAGICC (M'C) and the Third Assessment Report (TAR)

RFs for CO_2, CH_4 and SO_4 from LinClim compare favourably with both MAGICC and TAR data. However, whilst O_3 RF from LinClim compares well with data from TAR, it is significantly greater than that from MAGICC. However, the O_3 formulation within MAGICC is different to that of data from the TAR [7].

4 Data used in stabilization scenarios

The input data were those specified in the Innovation Modelling Comparison Project (IMCP) which is providing data and input to the IPCC Fourth Assessment Report (AR4). The 'baseline' scenario was the CPI (Common POLES-IMAGE) scenario developed by the National Institute for Public Health (RIVM) in the Netherlands and the Institute of Energy Policy and Economics (IEPE) in France [12].

MAGICC 4.1 was used to obtain CO_2 concentrations from the emissions provided. The default model parameters (except climate sensitivity of $\Delta T_{2x} = 2.5°C$) were used to produce concentration projections that were very similar to the ISAM and Bern carbon cycle models (as described in IPCC TAR [3]) were adopted in the MAGICC simulation. The remaining emissions were used from the SRES A1B Illustrative Scenario. Emissions of CH_4 and SO_2 were provided from the CPI scenario. Emissions of CO, NO_X, VOCs and soot were taken from SRES scenario A1B.

Concentration data of CO_2 for the stabilization scenarios were specified under the IMCP project. Only CO_2 concentrations were modified for the three stabilization scenarios. CH_4, CO, NO_X, and VOCs emissions data were obtained from the MAGICC WRE scenarios. These data corresponds to the P50 (median of all the SRES scenarios) emissions scenarios [13]. Emissions for SO_2 and soot were taken from SRES scenario A1B.

5 Results and discussion

In Figure 1, the RF (excluding RFs from N_2O and HCFCs) from the CPI baseline and WRE450, 500, and 550 scenarios is shown, without and with aviation. The aviation scenario used is the 'Fa1' scenario [1] that was based upon IS92a GDP assumptions. However, the initial trajectory of aviation growth is indicating that Fe1 (IS92e GDP assumptions) may be more realistic, certainly in the short term. We can see that the differences in total global RF from aviation is relatively small by 2100, e.g. aviation adds 3.7% by 2100 for the CPI baseline and 6.3% to the WRE450 scenario.

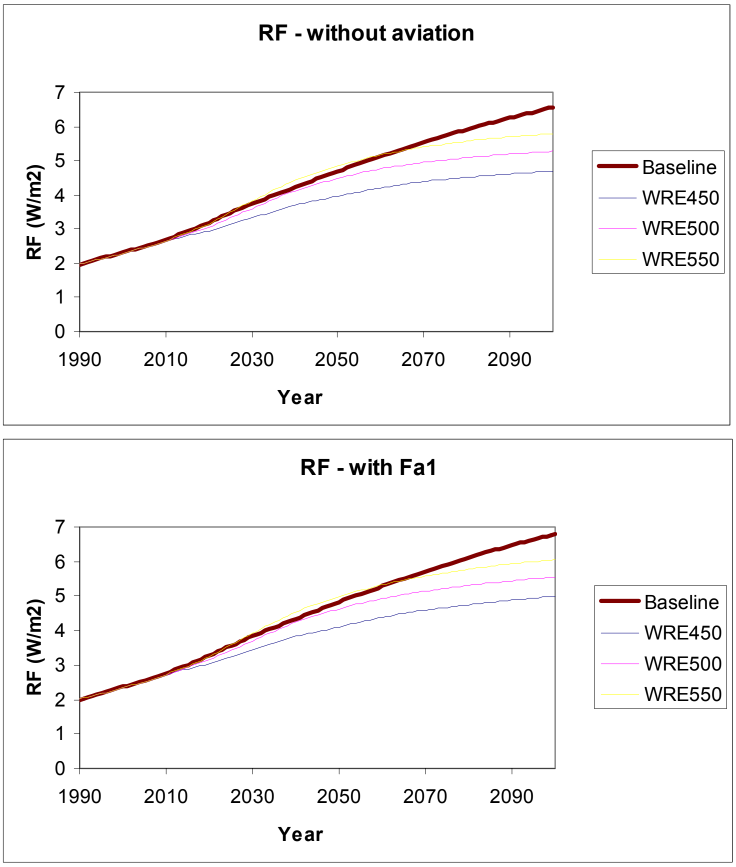
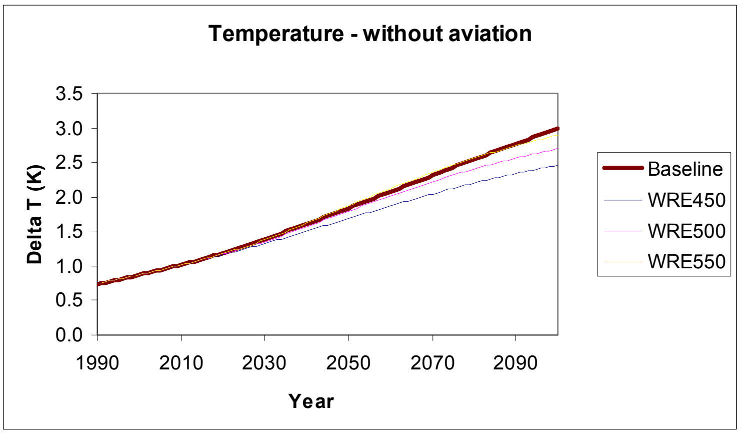


Figure 1 Comparison of total RF (see text) by 2100 with (Fa1) and without aviation emissions for CPI baseline and WRE scenarios

In Figure 2, the temperature response to 2100 is shown, again with and without aviation (Fa1). It should be noted that the temperature response excludes the effects of N_2O and HCFCs (similar to the RF calculations). Once more, the total global response is small but potentially significant. For example, aviation adds 5.8% by 2100 for the CPI baseline and 7.6% to the WRE450 scenario.



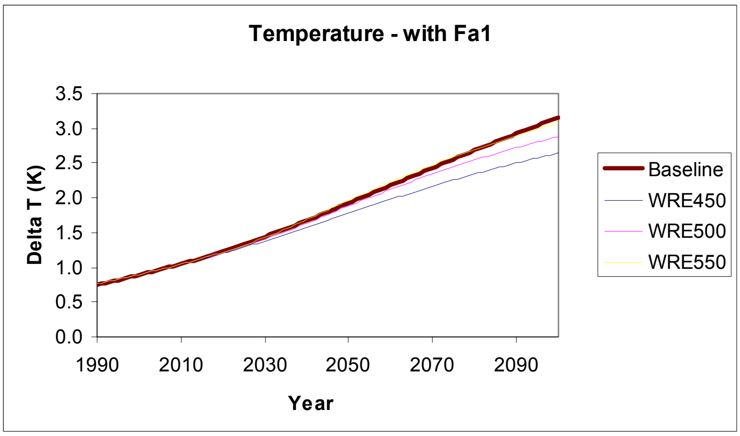


Figure 2 Comparison of total temperature response (see text) by 2100 with (Fa1) and without aviation emissions for CPI baseline and WRE scenarios

Whilst the RF and temperature responses are small, globally, the WRE scenarios do not consider sectoral disaggregation. The underlying assumption currently seems to be that emissions trading of aviation CO_2 is an appropriate policy measure. The reason for this is that it essentially allows aviation to grow, purchasing permits from saving made elsewhere. The consequence of this relatively unconstrained market-demand driven growth is that for some countries, especially those that are large international 'hubs', such as the UK, aviation could represent a large fraction of emission allocations to achieve stabilization. The UK has committed to cutting CO_2 emissions by 2050 on 1990 levels. The underlying basis for this was climate stabilization. If the currently unallocated international UK aviation emissions are added on to the UK CO_2 budget, Figure 3 shows these emissions under 3 simple growth rate scenarios, which imply that aviation could consume 22%, 39% or 67% of the UK's CO_2 budget in 2050 for 3%, 4% and 5% growth rates. This was calculated using a sophisticated global aviation inventory tool, FAST (see [14, 15]), allocating UK international emissions by SBSTA Method 5 (see [1], chapter 10) and assuming historically-based assumptions on fuel efficiency. The assumptions on growth rates are simplistic and intended to be illustrative, although the central estimate of 39% is not too different from DFT projections which have more refined growth assumptions but much simpler fuel calculation methods.

Of course, overlaying a 'business-as-usual' aviation emissions scenario on a stabilization emissions scenario is inconsistent as the broad assumption of the latter assumes cross-sectoral emissions reductions. However, the study is intended to be hypothetical and to draw attention to the implications of allowing aviation emissions to develop in a 'free-flying' society, whilst demanding emissions reductions from other sectors to achieve climate stabilization. Moreover, it is necessary at some point to consider how stabilization scenarios might be achieved from a 'bottom-up' estimation of emissions, which has not been considered thus far. This study shows how difficult this might be under the assumption of a 'free-flying' society and draws attention to the necessity to consider stabilization from a sectoral point of view where societal choices come into sharp focus.

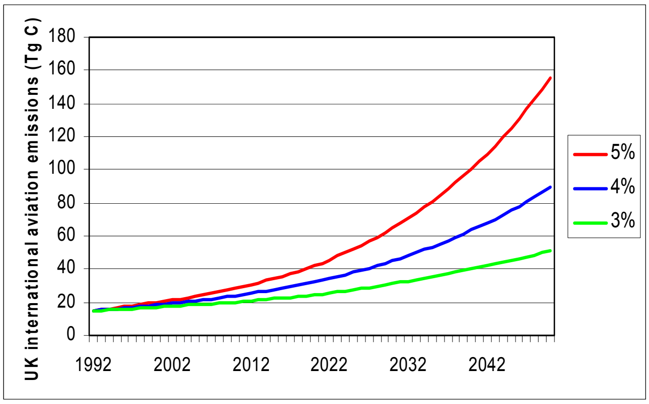


Figure 3 Projected development of UK international aviation emissions of CO_2 at different assumed annual growth rates

6 Conclusions

Adding on the IPCC Fa1 central aviation scenario to the baseline, WRE450, 500 and 550 stabilization scenarios results in an extra forcing of 3.7%, 6.3%, 5.3%, 4.6% W m^{-2} over the same scenarios without aviation, respectively and an increased temperature response of 5.8%, 7.6%, 6.7%, 6.1% over the baseline, WRE450, 500 and 550 scenarios. These are small but significant global increases over the WRE scenarios. Whilst the global response is very small, there are potentially significant implications for countries in the three major centres of aviation (North America, Europe, Far East) where aviation emissions under this hypothetical business-as-usual aviation scenario overlaid on WRE scenarios. If aviation emissions are allowed to increase in this manner whilst striving for stabilization, this implies that strong reductions of CO_2 emissions must be made in other sectors and that aviation could constitute significant fractions of an individual country's CO_2 emissions allocation. Using the illustrative example of the UK, it is possible that aviation might constitute somewhere between 22% and 67% of the UK's CO_2 budget by 2050 under simplified growth assumptions. Whether emissions trading will stimulate the kind of reductions necessary in other sectors under this scenario of an unconstrained 'flying society' remains to be seen.

References

[1] IPCC (1999) Aviation and the Global Atmosphere, Penner JE, Lister DH, Griggs DJ, Dokken DJ and McFarland M (eds). Intergovernmental Panel on Climate Change, Cambridge University Press, UK.

[2] Sausen R, Isaksen I, Grewe V, Lee DS, Myhre G, Schumann U, Stordal F and Zerefos C (2005) Aviation Radiative Forcing in 2000: An Update on IPCC (1999) *Meteorologische Zeitschrift* (submitted).

[3] IPCC (2001) Climate Change 2001, the Scientific Basis. Cambridge University Press, UK.

[4] Sausen R and Schumann U (2000) Estimates of the climate response to aircraft CO_2 and NO_X emissions scenarios. *Climate Change* 44, 27–58.

[5] Raper SCB, Wigley TML and Warrick RA (1996) Global sea level rise: past and future. In '*Sea-Level Rise and Coastal Subsidence: Causes, Consequences and Strategies*' (eds Milliman J and Haq BU), Kluwer Academic Publishers, Dordrecht, The Netherlands, 11–45.

[6] Wigley TML, Richels R and Edmonds JA (1996) Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature* 379, 240–243.

[7] Wigley TML and Raper SCB (2001) Interpretation of high projections for global-mean warming. *Science* 293, 451–454.

[8] Wigley TML and Raper SCB (2002) Reasons for larger warming projections in the IPCC Third Assessment Report. *Journal of Climate* 15, 2945–2952.

[9] Hasselmann K, Sausen R, Maier-Reimer E and Voss R (1993). On the Cold Start Problem in Transient Simulations with Coupled Atmosphere-Ocean Models. *Climate Dynamics* 9, 53-61.

[10] Lim LL, Lee DS, Sausen R and Ponater M (2005) Calculating radiative forcing and temperature changes from aviation effects with a climate response model. In preparation.

[11] Wigley TML, Smith SJ and Prather MJ (2002). Radiative forcing due to reactive gas emissions. *Journal of Climate* 15, 2690–2696.

[12] Criqui P, Kitous A, Berk M, den Elzen M, Eickhout B, Lucas P, van Vuuren D, Kouvaritakis N and Vanregemorter D (2003) Greenhouse Gas Reduction Pathways in the UNFCCC Process up to 2025. Technical Report. Study Contract: B4-3040/2001/325703/MAR/E.1 for the DG Environment.

[13] Wigley TML (2003) MAGICC/SCENGEN 4.1 User Manual

[14] Fichter C, Marquart S, Sausen R and Lee DS (2005) The impact of cruise altitude on contrails. *Meteorologische Zeitschrift* (submitted)

[15] Stordal F, Myhre G, Arlander DW, Svendby T, Stordal EJG, Rossow WB and Lee DS (2004) Is there a trend in cirrus cloud cover due to aircraft traffic? *Atmospheric Physics and Chemistry Discussions*