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Aviation and global climate change in the 21st century

David S. Lee [a,*], David W. Fahey [b], Piers M. Forster [c], Peter J. Newton [d], Ron C.N. Wit [e], Ling L. Lim [a], Bethan Owen [a], Robert Sausen [f]

[a] Dalton Research Institute, Manchester Metropolitan University, John Dalton Building, Chester Street, Manchester M1 5GD, United Kingdom
[b] NOAA Earth System Research Laboratory, Chemical Sciences Division, Boulder, CO, USA
[c] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom
[d] Department for Business, Enterprise and Regulatory Reform, Aviation Directorate, United Kingdom
[e] Natuur en Milieu, Donkerstraat 17, Utrecht, The Netherlands
[f] Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

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ABSTRACT

Aviation emissions contribute to the radiative forcing (RF) of climate. Of importance are emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), aerosols and their precursors (soot and sulphate), and increased cloudiness in the form of persistent linear contrails and induced-cirrus cloudiness. The recent Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) quantified aviation's RF contribution for 2005 based upon 2000 operations data. Aviation has grown strongly over the past years, despite world-changing events in the early 2000s; the average annual passenger traffic growth rate was 5.3% yr^{-1} between 2000 and 2007, resulting in an increase of passenger traffic of 38%. Presented here are updated values of aviation RF for 2005 based upon new operations data that show an increase in traffic of 22.5%, fuel use of 8.4% and total aviation RF of 14% (excluding induced-cirrus enhancement) over the period 2000–2005. The lack of physical process models and adequate observational data for aviation-induced cirrus effects limit confidence in quantifying their RF contribution. Total aviation RF (excluding induced cirrus) in 2005 was ~55 mW m^{-2} (23–87 mW m^{-2}, 90% likelihood range), which was 3.5% (range 1.3–10%, 90% likelihood range) of total anthropogenic forcing. Including estimates for aviation-induced cirrus RF increases the total aviation RF in 2005–78 mW m^{-2} (38–139 mW m^{-2}, 90% likelihood range), which represents 4.9% of total anthropogenic forcing (2–14%, 90% likelihood range). Future scenarios of aviation emissions for 2050 that are consistent with IPCC SRES A1 and B2 scenario assumptions have been presented that show an increase of fuel usage by factors of 2.7–3.9 over 2000. Simplified calculations of total aviation RF in 2050 indicate increases by factors of 3.0–4.0 over the 2000 value, representing 4–4.7% of total RF (excluding induced cirrus). An examination of a range of future technological options shows that substantive reductions in aviation fuel usage are possible only with the introduction of radical technologies. Incorporation of aviation into an emissions trading system offers the potential for overall (i.e., beyond the aviation sector) CO_2 emissions reductions. Proposals exist for introduction of such a system at a European level, but no agreement has been reached at a global level.

1. Introduction

The interest in aviation's effects on climate dates back some decades. For example, literature on the potential effects of contrails can be traced back as far as the late 1960s and early 1970s (Reinking, 1968; Kuhn, 1970; SMIC, 1971). However, the initial concern over aviation's global impacts in the early 1970s was related to potential stratospheric ozone (O_3) depletion from a proposed fleet of civil supersonic aircraft (e.g., SMIC, 1971), which in the event, was limited to the Concorde and Tupolev-144.

In the late 1980s and early 1990s, research was initiated into the effects of nitrogen oxide emissions ($NO_x = NO + NO_2$) on the formation of tropospheric O_3 (a greenhouse gas) and to a lesser extent, contrails, from the current subsonic fleet. The EU AERONOX and the US SASS projects (Schumann, 1997; Friedl et al., 1997) and a variety of other research programmes identified a number of emissions and effects from aviation, other than those from CO_2, which might influence climate, including the emission of particles and the effects of contrails and other aviation-induced cloudiness (AIC, hereafter). In assessing the potential of anthropogenic activities

* Corresponding author.
E-mail address: d.s.Lee@mmu.ac.uk (D.S. Lee).

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to affect climate, aviation stands out as a unique sector since the largest fraction of its emissions are injected at aircraft cruise altitudes of 8–12 km. At these altitudes, the emissions have increased effectiveness to cause chemical and aerosol effects relevant to climate forcing (e.g., cloud formation and O_3 production).

In 1999, one year after a European assessment of the atmospheric impact of aviation (Brasseur et al., 1998), the Intergovernmental Panel on Climate Change (IPCC) published a landmark report, '*Aviation and the Global Atmosphere*' (IPCC, 1999), which presented the first comprehensive assessment of aviation's impacts on climate using the climate metric 'radiative forcing' (Prather et al., 1999). Radiative forcing (RF) is a measure of the perturbation of the Earth-atmosphere energy budget since 1750 (by convention in IPCC usage) resulting from changes in trace gases and particles in the atmosphere and other effects such as changed albedo, and is measured in units of watts per square metre ($W m^{-2}$) at the top of the atmosphere. The RF components from aviation arise from the following processes:

- emission of CO_2, (positive RF);
- emission of NO_x (positive RF). This term is the sum of three component terms: production of tropospheric O_3 (positive RF); a longer-term reduction in ambient methane (CH_4) (negative RF), and a further longer-term small decrease in O_3 (negative RF);
- emissions of H_2O (positive RF);
- formation of persistent linear contrails (positive RF);
- aviation-induced cloudiness (AIC; potentially a positive RF);
- emission of sulphate particles (negative RF); and,
- emission of soot particles (positive RF).

These emissions and cloud effects modify the chemical and particle microphysical properties of the upper atmosphere, resulting in changes in RF of the earth's climate system, which can potentially lead to climate change impacts and ultimately result in damage and welfare/ecosystem loss as illustrated in Fig. 1. The IPCC (1999) report concluded that aviation represents a small but potentially significant and increasing forcing of climate that is somewhat uncertain in overall magnitude, largely because of its non-CO_2 effects. The IPCC (1999) estimated that aviation represented 3.5% of the total anthropogenic RF in 1992 (excluding AIC), which was projected to increase to 5% for a mid-range emission scenario by 2050.

The RF effects of aviation were re-evaluated quantitatively by Sausen et al. (2005) for the year 2000, which resulted in a total RF of 47.8 mW m^{-2} (excluding AIC), which was not dissimilar to that given by the IPCC (1999) for 1992 traffic (48.5 mW m^{-2}, excluding AIC), despite the increase in traffic over the period 1992–2000. This was largely the result of more realistic assumptions underlying the calculation of contrail RF (which was reduced by more than a factor of three from 33 mW m^{-2} to 10 mW m^{-2} if 1992 traffic is scaled to 2000) and the improvements over the intervening period to the models that were used to assess NO_x impacts. For AIC, Sausen et al. (2005) adopted the mean estimate of Stordal et al. (2005) of 30 mW m^{-2}, with an uncertainty range of 10–80 mW m^{-2}. The upper limit of 80 mW m^{-2} for AIC was twice that given by IPCC (1999).

More recently, RFs from all the major greenhouse gases and other effects were reassessed by the IPCC for the Fourth Assessment Report (AR4) by Working Group one (WGI) for a base year of 2005

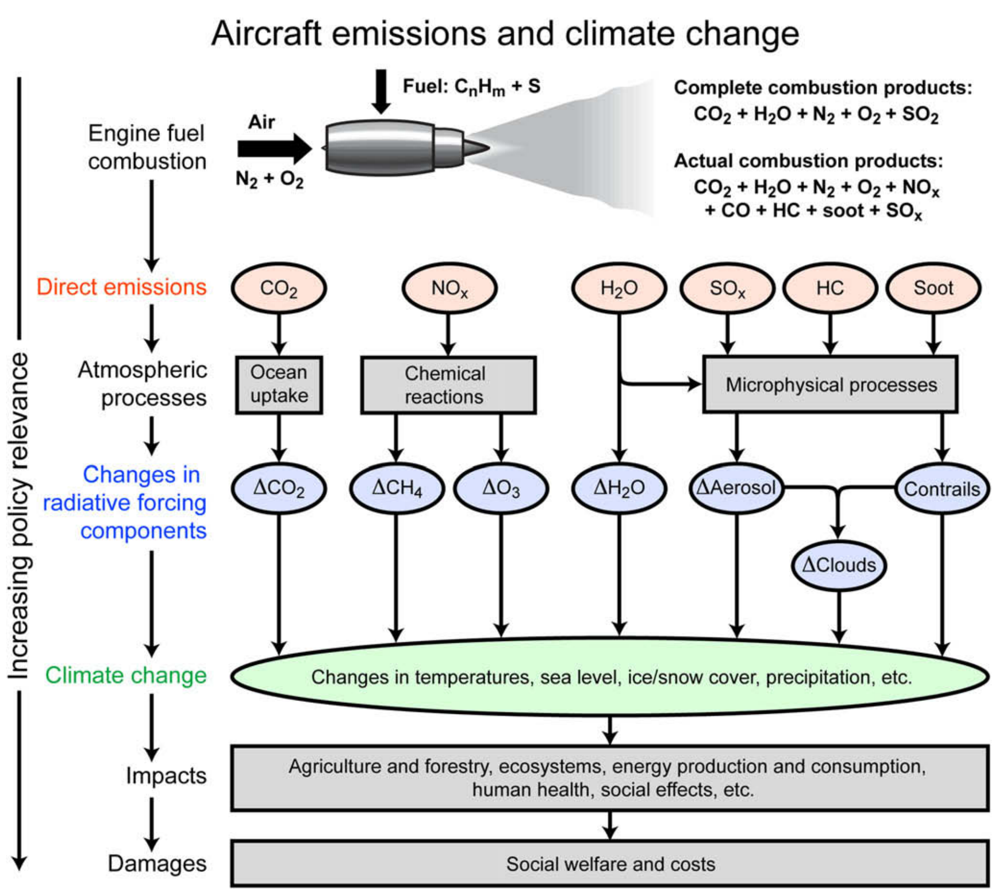

Fig. 1. Schema showing the principal emissions from aviation operations and the atmospheric processes that lead to changes in radiative forcing components. Radiative forcing changes lead to climate change as measured by temperatures and sea levels, for example. Climate change creates impacts on human activities and ecosystems and can lead to societal damages. Adapted from Prather et al. (1999) and Wuebbles et al. (2007).