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Transport impacts on atmosphere and climate: Aviation

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A B S T R A C T

Aviation alters the composition of the atmosphere globally and can thus drive climate change and ozone depletion. The last major international assessment of these impacts was made by the Intergovernmental Panel on Climate Change (IPCC) in 1999. Here, a comprehensive updated assessment of aviation is provided. Scientific advances since the 1999 assessment have reduced key uncertainties, sharpening the quantitative evaluation, yet the basic conclusions remain the same. The climate impact of aviation is driven by long-term impacts from CO_2 emissions and shorter-term impacts from non-CO_2 emissions and effects, which include the emissions of water vapour, particles and nitrogen oxides (NO_x). The present-day radiative forcing from aviation (2005) is estimated to be 55 mW m^{-2} (excluding cirrus cloud enhancement), which represents some 3.5% (range 1.3–10%, 90% likelihood range) of current anthropogenic forcing, or 78 mW m^{-2} including cirrus cloud enhancement, representing 4.9% of current forcing (range 2–14%, 90% likelihood range). According to two SRES-compatible scenarios, future forcings may increase by factors of 3–4 over 2000 levels, in 2050. The effects of aviation emissions of CO_2 on global mean surface temperature last for many hundreds of years (in common with other sources), whilst its non-CO_2 effects on temperature last for decades. Much progress has been made in the last ten years on characterizing emissions, although major uncertainties remain over the nature of particles. Emissions of NO_x result in production of ozone, a climate warming gas, and the reduction of ambient methane (a cooling effect) although the overall balance is warming, based upon current understanding. These NO_x emissions from current subsonic aviation do not appear to deplete stratospheric ozone. Despite the progress made on modelling aviation's impacts on tropospheric chemistry, there remains a significant spread in model results. The knowledge of aviation's impacts on cloudiness has also improved: a limited number of studies have demonstrated an increase in cirrus cloud attributable to aviation although the magnitude varies: however, these trend analyses may be impacted by satellite artefacts. The effect of aviation particles on clouds (with and without contrails) may give rise to either a positive forcing or a negative forcing: the modelling and the underlying processes are highly uncertain, although the overall effect of contrails and enhanced cloudiness is considered to be a positive forcing and could be substantial, compared with other effects. The debate over quantification of aviation impacts has also progressed towards studying potential mitigation and the technological and atmospheric tradeoffs. Current studies are still relatively immature and more work is required to determine optimal technological development paths, which is an aspect that atmospheric science has much to contribute. In terms of alternative fuels, liquid hydrogen represents a possibility and may reduce some of aviation's impacts on climate if the fuel is produced in a carbon-neutral way: such fuel is unlikely to be utilized until a 'hydrogen economy'

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develops. The introduction of biofuels as a means of reducing CO_2 impacts represents a future possibility. However, even over and above land-use concerns and greenhouse gas budget issues, aviation fuels require strict adherence to safety standards and thus require extra processing compared with biofuels destined for other sectors, where the uptake of such fuel may be more beneficial in the first instance.

1. Introduction

This report constitutes the aviation assessment component of the European 6th Framework project 'ATTICA', the '*European Assessment of Transport Impacts on Climate Change and Ozone Depletion*'. Partner assessments of surface transportation, shipping, and climate metrics are given by Uherek et al. (2009), Eyring et al. (2009), and Fuglestvedt et al. (2010), respectively.

Previously, the most complete and up to date assessment of aviation's impacts on climate change and ozone (O_3) depletion was that undertaken by the Intergovernmental Panel on Climate Change (IPCC) and published as a Special Report; '*Aviation and the Global Atmosphere*' (IPCC, 1999). The IPCC (1999) report had been preceded by a number of assessments of the effects of subsonic aviation on the atmosphere, e.g. Wahner et al. (1995), Friedl (1997) and Brasseur et al. (1998). Over the last 15 years or so, there has been considerable activity investigating aviation's effects on the global atmosphere in national and international research programmes, including dedicated efforts for the IPCC (1999) report. Shortly before the completion of the IPCC (1999) assessment, Boeing announced that it no longer intended to pursue development of a large supersonic aircraft, largely on grounds of economics and noise impacts. In addition, the aeronautics program at NASA was folded into the space shuttle program. The pioneering dedicated research programmes by NASA into effects from both potential future supersonic fleets and subsonic aviation were terminated.

In Europe, however, the main findings of the IPCC (1999) report, and in particular the magnitude of the non-CO_2 RF effects, estimated by the IPCC (1999) to be 63% of the total radiative effect from aviation in 1992 (excluding cirrus cloud enhancement), provided a springboard from which a number of research programmes into atmospheric science and 'green' aeronautical technology were initiated under the European Commission's Fifth Framework Programme. These programmes include: PartEmis, NEPAIR, TRADEOFF, INCA, AERO2K, METRIC, SCENIC and CRYOPLANE (see Appendix I). The bulk of the efforts of these programmes were directed at subsonic effects/technology, with the exception of SCENIC and minor components of TRADEOFF. CRYOPLANE focussed on the potential for future liquid hydrogen (LH_2) powered aircraft. In addition, a number of other related European Fifth Framework Projects were initiated studying the nitrogen budget in the upper troposphere from natural sources, especially lightning (LINOX, EULINOX, TROCCINOX), which have been summarized by Schumann and Huntrieser (2007). European Commission research efforts into aviation effects have continued through the Sixth Framework Integrated Project 'QUANTIFY', which runs until 2009.

By convention, the interest in aviation's impacts on climate change and ozone depletion are thought to date back some 40 years to the late 1960s when the US and UK were developing ideas for supersonic aircraft and concerns were raised over stratospheric O_3 depletion (Johnston, 1971). However, there is evidence dating back to the early 1960s of awareness that air traffic might modify climate through contrails (condensation trails) (Osmundsen, 1963). The possibility that aviation might affect tropospheric O_3 and climate appears to have been first considered during the early stratospheric assessments undertaken in the US, UK and France in the early to mid 1970s (e.g. the CIAP, COMESA and COVOS programmes) with the increasing recognition that tropospheric O_3 was a climate warming gas (Ramanathan and Dickinson, 1979; Wang et al., 1980; Lacis and WuebblesLogan, 1990). The earliest paper that identifies aircraft NO_x increasing tropospheric O_3 is not clear but early literature includes Hidalgo (1977), Hidalgo and Crutzen (1977) and Widhopf et al. (1977) following earlier recognition of a 'cross-over' from O_3 production from NO_x in the troposphere to O_3 destruction in the stratosphere by Johnston and Quitevis (1974).

After initial concerns over potential stratospheric O_3 depletion in the early 1970s from a proposed large fleet of supersonic aircraft (which was never developed), attention shifted in the early 1990s to O_3 enhancement in the upper troposphere and lower stratosphere (UT/LS) (where O_3 is a strong greenhouse gas) resulting from subsonic aircraft emissions of NO_x ($NO + NO_2$) (Johnston et al., 1991). Subsequently, much research has been focussed over the last 10 years on contrails and cirrus cloud enhancement. The IPCC (1999) report pointed out that the potential contribution from subsonic aviation for a range of 2050 scenarios could be between 3 and 7% of total radiative forcing, excluding cirrus cloud enhancement (Chapter 6; Prather et al., 1999). The IPCC Fourth Assessment Report considered aviation but only briefly: Working Group 1 (IPCC, 2007a) provided a short overview of literature on contrails and cirrus cloud enhancement (Chapter 2; Forster et al., 2007a) and Working Group 3 (IPCC, 2007b) reviewed technological mitigation potential (Chapter 5; Kahn-Ribeiro et al., 2007).

Sufficient concerns remain both in terms of the science and the policy (principally because of the historically strong growth rate of aviation and the fact that international aviation is not included in the Kyoto Protocol) over the potential magnitude of future aviation emissions and their contribution to climate change. Thus, a further state-of-the-art assessment updating that of IPCC (1999) was considered necessary, since much important material has been published since then.

The ATTICA aviation assessment focuses on the science: in terms of the policy, only the backdrop of aviation's impacts with respect to other sources and its potential growth in emissions will be addressed. Questions as to whether, why and how aviation emissions should be addressed through policy action are not covered here, although the metrics by which aviation emissions and their effects may be compared with those from other sources is an ongoing scientific debate, covered in more detail by the ATTICA climate metric assessment (Fuglestvedt et al., 2009) but also briefly dealt with here for completeness.

2. The effects of aviation on climate change and ozone depletion

The climate impact of current and potential future aviation is, by convention, quantified using the metric 'radiative forcing of climate', since many climate experiments have found an approximately linear relationship between a change in global mean radiative forcing (RF) and a change in global mean surface temperature (ΔT_s), when the system has reached a new equilibrium, with some proportionality constant, i.e.

$$\Delta T_s \approx \lambda \mathrm{RF} \quad (1)$$

where λ is the climate sensitivity parameter (K (W m^{-2})$^{-1}$), the value of which has been found to be model specific but stable across