View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Institute of Transport Research:Publications

Atmospheric Environment 43 (2009) 3520–3537

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

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

ARTICLE INFO

Article history:
Received 19 November 2008
Received in revised form
7 April 2009
Accepted 8 April 2009

Keywords:
Aviation
Aviation emissions
Aviation trends
Climate change
Radiative forcing
Contrails
Aviation-induced cirrus
IPCC
AR4
Climate change mitigation
Climate change adaptation

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.

© 2009 Elsevier Ltd. All rights reserved.

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).

1352-2310/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.atmosenv.2009.04.024

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

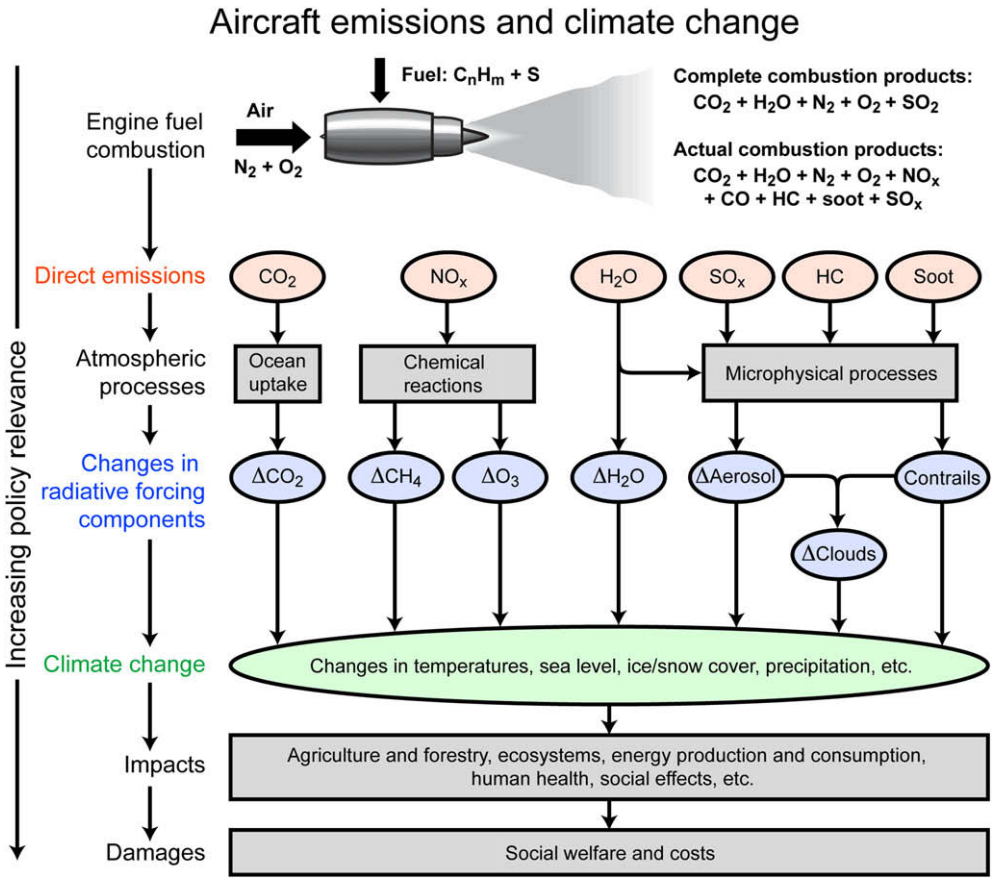

Fig. 1. Schema showing the principal emissions from aviation operations and the atmospheric processes that lead to changes in radiative forcing components. Radiative forcing changes lead to climate change as measured by temperatures and sea levels, for example. Climate change creates impacts on human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

(Forster et al., 2007a). Forster et al. (2007a) were unable to update the aviation forcings from Sausen et al. (2005) as fuel scalar data were not available. Instead, the Sausen et al., 2005 RF values were adopted as 2005 values, noting that they would likely to be within ±10% of the actual 2005 value. IPCC's Working Group three (WGIII), in conjunction with WGI, estimated that aviation represented 3% of the total anthropogenic RF in 2005, with an uncertainty range based on non-aviation forcings of 2–8% (Kahn-Ribeiro et al., 2007). The uncertainty range was set by the background anthropogenic RF rather than aviation effects, since Sausen et al. (2005) did not report uncertainties for aviation RF components.

Aviation passenger transport volume in terms of revenue passenger kilometres (RPK) has continued to grow strongly at an average rate of 5.2% per annum over the period 1992–2005, despite world-changing events such as the first Gulf War, the World Trade Center attack and outbreaks of Severe Acute Respiratory Syndrome (SARS) (Fig. 2). Aircraft manufacturers predict that the global civil fleet may nearly double from ~20,500 aircraft in 2006–~40,500 aircraft in 2026 (Airbus, 2007). Meanwhile, because of the strong growth rate of aviation and the resulting policy interests in mitigating potential future increases in emissions, climate research has continued since the IPCC (1999) report with the objective of reducing

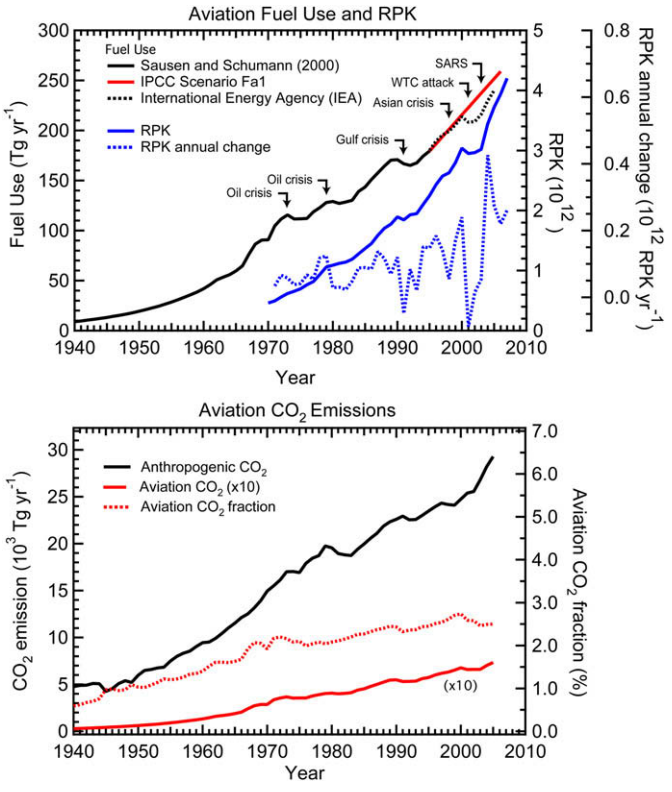

Fig. 2. (Top) Aviation fuel usage beginning in 1940 from Sausen and Schumann (2000) and extended with data from IEA (2007) and the IPCC Fa1 scenario of Henderson et al. (1999). The arrows indicate world events that potentially threatened global aviation use: the oil crises of the 1970s, the Gulf war crisis in the early 1990s, the Asian financial crisis in the late 1990s, the World Trade Center (WTO) attack in 2001 and the global health crisis brought about by the severe acute respiratory syndrome (SARS). Also shown is the growth in air passenger traffic from 1970 to 2007 in billions (10^{12}) of revenue passenger kilometres (RPK) (near right hand axis) (source: ICAO traffic statistics from http://www.airlines.org/economics/traffic/World+Airline+Traffic.htm accessed, 19 Sept. 2007) and the annual change in RPK (far right hand axis (Note offset zero)) (Bottom) Growth in CO_2 emissions in Tg CO_2 yr^{-1} for all anthropogenic activities and from aviation fuel burn (left hand axis), and the fraction of total anthropogenic CO_2 emissions represented by aviation CO_2 emissions (%) (right hand axis). Note ×10 scaling of aviation CO_2 emissions.

the uncertainties of aviation's non-CO_2 effects, particularly the effects of linear persistent contrails and AIC.

Whereas it was concluded in the IPCC AR4 WGI report that aviation's total RF in 2005 was within ±10% of 2000 values because of slow growth in aviation fuel usage over the 2000–2005 period, recently available air traffic data from the International Civil Aviation Organization (ICAO) and kerosene fuel sales data from the International Energy Agency (IEA, 2007) indicate strong increases in aviation activity and associated CO_2 emissions over this period. These new data provided the initial motivation for the present study. In the following we recalculate aviation 2005 RFs, assess uncertainties, provide new illustrative scenarios of 2050 aviation emissions and RFs, and examine potential mitigation opportunities afforded by technological improvements and policy-measures.

2. Aviation radiative forcing in the IPCC Fourth Assessment Report

2.1. Context

The IPCC AR4 WGI remit was to consider total anthropogenic and natural RFs for 2005, updating estimates for 2000 provided in the Third Assessment Report (IPCC, 2001). The only RF components for aviation considered explicitly were persistent linear contrails and AIC, since other aviation contributions (e.g., CO_2, O_3/CH_4, etc) were included in data and model calculations that treated these other effects. The current state of knowledge of contrail and AIC RFs as assessed by IPCC AR4 and the use of metrics for aviation are summarized in the following sections.

2.2. Contrail radiative forcing

The IPCC AR4 WGI estimate for contrail RF was based upon the work of Sausen et al. (2005) and references therein, which reassessed aviation for the year 2000 and provided a best estimate for persistent linear contrails of 10 mW m^{-2}. (A 'best' estimate is that estimate resulting from the IPCC assessment process and is usually associated with an uncertainty following IPCC nomenclature. See the Technical Summary of IPCC AR4 WGI (p.23) (IPCC, 2007).) This value is approximately a factor of three smaller than the contrail RF (33 mW m^{-2}) that Sausen et al. (2005) obtained for 2000 by scaling the IPCC (1999) figures. The smaller estimate arises principally from recalculations of contrail coverage and space and time dependent optical depths, which have almost linear effects on the calculation of overall forcing (noting that contrail RF is the sum of two forcings, infrared and visible radiation, which have opposite signs). There remain significant uncertainties over contrail coverage and the optical depth of contrails (Schumann, 2005; Forster et al., 2007a). The uncertainties in the contrail coverage arise from the lack of global observations of contrails and the poorly known extent of ice-supersaturation in the upper atmosphere. Ice-supersaturation in the ambient atmosphere along an aircraft flight track is required for the formation of a persistent contrail. Ice-supersaturation is only measured locally with instrumental difficulty (e.g., Spichtinger et al., 2003) and estimated with significant uncertainty by global atmospheric models, although effort is being committed to improving this (Tompkins et al., 2007). The uncertainties in the optical depth derive from uncertainties in the size distribution, number concentration, and shape of ice crystals.

2.3. Aviation-induced cirrus cloud radiative forcing

Aviation-induced cirrus cloud cover is thought to arise from two different mechanisms. The first (direct) mechanism is the formation of persistent linear contrails, which can spread through wind-shear to form cirrus-like cloud structures, sometimes called contrail-

cirrus, that are eventually indistinguishable from natural cirrus. A limited number of studies have provided estimates of trends in both contrails and AIC based on satellite data of cloudiness trends (Stordal et al., 2005; Stubenrauch and Schumann, 2005; Zerefos et al., 2003; Eleftheratos et al., 2007). The second (indirect) mechanism is the accumulation in the atmosphere of particles emitted by aircraft at cruise altitudes, namely those containing black carbon, sulphate and organic compounds (Kärcher et al., 2000) that may act as cloud condensation nuclei. Here, the term aviation-induced cloudiness (AIC) is used to include both these mechanisms. Atmospheric models have shown that black carbon particles from aircraft could either increase or decrease the number density of ice crystals in cirrus, depending on assumptions about the ice nucleation behaviour of the atmospheric (non-aircraft) aerosol in cirrus conditions (Hendricks et al., 2005). A change in the upper-tropospheric ice nuclei abundance or nucleation efficiency can lead to changes in cirrus cloud properties (Kärcher et al., 2007), including their frequency of formation and optical properties, which in turn changes the RF contribution of cloudiness in the upper atmosphere.

On the basis of correlation analyses, two studies (Zerefos et al., 2003; Stordal et al., 2005) attributed observed decadal trends in cirrus cloud coverage to aviation from spreading linear contrails and their indirect effect. Both these studies used the International Satellite Cloud Climatology Project (ISCCP) database and derived cirrus cloud trends for Europe of 1–2% per decade over the last two decades. A further study using different instrumental remote measurements provided support for such trends (Stubenrauch and Schumann, 2005) but not their magnitude, finding a trend approximately one order of magnitude smaller than those of Zerefos et al. (2003) and Stordal et al. (2005). Stordal et al. (2005) estimated a global RF for aviation cirrus with a mean value of 30 mW m^{-2} and an uncertainty range of 10–80 mW m^{-2}, assuming similar optical properties to very thin cirrus. IPCC AR4 WGI adopted these values with the caveat that 30 mW m^{-2} does not constitute a 'best estimate' in the same qualitative sense as other evaluated components of anthropogenic climate forcing. Nonetheless, 30 mW m^{-2} is in reasonable agreement with the upper limit value of 1992 aviation-cirrus forcing of 26 mW m^{-2} estimated by Minnis et al. (2004).

2.4. Climate metrics for comparing emissions from aviation

Radiative forcing is used here, as in previous studies, as the preferred metric for quantifying the climate impact of aviation at a given point in time as a result of historical and current emissions. However, alternative metrics have been discussed for aviation and other sectors. There has been considerable debate on the subject of emission equivalences, with Fuglestvedt et al. (2003, in press) providing comprehensive reviews. The usage of Global Warming Potentials (GWPs) for aviation non-CO_2 emissions was not considered specifically by WGI (Forster et al., 2007a), as did Prather et al. (1999), but were considered in the context of comparing GWPs from short-lived (e.g., O_3) and long-lived species. Nonetheless, several of the studies reviewed by IPCC AR4 WGI (Forster et al., 2007a) considered O_3 and CH_4 changes from aviation NO_x (Derwent et al., 2001; Stevenson et al., 2004; Wild et al., 2001). The difficulty in formulating a robust GWP for aviation NO_x emissions was revealed in that whilst all three aforementioned studies consistently found positive AGWPs for the primary O_3 increases and negative AGWPs for CH_4 and secondary O_3 decreases, the balance of these terms was 100 and 130 in two of the studies, and −3 in the third.

In order to illustrate that aviation has significant climate forcings beyond the emission of long-lived greenhouse gases, Prather et al. (1999) introduced the concept of the Radiative Forcing Index (RFI), which is the total aviation RF divided by the aviation CO_2 RF. However, the RFI is not an emissions multiplier that can be used to account for aviation's non-CO_2 effects from future emissions. This was confirmed by IPCC AR4 WGI (Forster et al., 2007a) in noting that the RFI cannot account for the different atmospheric lifetimes of the different forcing agents involved, as previously explained by Wit et al. (2005) and Forster et al. (2006, 2007b). However, no criticism *per se* was made of the RFI metric when it is properly understood and used. IPCC AR4 WGIII (Kahn-Ribeiro et al., 2007) clearly restated that "Aviation has a larger impact on radiative forcing than that from its CO_2 forcing alone".

The difficulties involved in the inclusion of non-CO_2 emissions and effects into policy frameworks have been highlighted by IPCC AR4 WGIII (Kahn-Ribeiro et al., 2007) and others (e.g., Wit et al., 2005; Forster et al., 2006, 2007b). Thus far, a suitable metric to put non-CO_2 radiative effects on an equivalent emissions basis to CO_2 for future aviation emissions has not been agreed upon because of the difficulties of treating short-lived species and a long-lived species such as CO_2 in an equivalent manner. The metric used to compare the climate impacts of long-lived GHG emissions under the Kyoto Protocol is 'equivalent CO_2 emissions' (i.e., emissions weighted with a 100-yr time horizon GWP). The equivalent-CO_2 emission metric is a forward-looking metric, calculated for an emission pulse and, hence, suitable for comparing future emissions in a policy context. The RFI metric is primarily a backward looking metric because it can only be used correctly with accumulated emissions of CO_2 and therefore is inherently unsuitable as an emissions-equivalency metric for policy purposes. In terms of non-CO_2 effects of aviation, the best current option may be to employ an additional policy instrument(s) that would address these effects directly.

3. Updating aviation radiative forcing in 2005

3.1. Aviation traffic and updated aviation fuel use for 2005

Aviation traffic volume is reported, by convention, in RPK. There have been clear upward trends in both RPK and available seat kilometres (ASK, a measure of capacity *cf.* utilization) over decadal timeframes but also over the period 2000–2005 (see Fig. 2), which would also imply an increase in fuel usage. As an accurate basis to update aviation RFs for 2005, recent kerosene fuel sales data for aviation operations were obtained from the IEA (IEA, 2007). These data were used to extend and update a time-series of fuel usage between 1940 and 1995 (Sausen and Schumann, 2000) to 2005.

Global civil air traffic declined in 2001 from 2000 levels in terms of RPK, after which there was a small recovery in 2002, followed by an increase of ~2% from 2002 to 2003 (Fig. 2). From 2003 to 2004, there was an unprecedented increase of 14% and a growth of 8% between 2004 and 2005 such that overall, traffic increased by 22.5% (38%) between 2000 and 2005 (2007), although there are strong regional differences (Airbus, 2007). Correspondingly, aviation fuel usage increased by 8.4% in 2005 over that in 2000 according to IEA statistics.

Various historical and projected aviation global CO_2 inventories are shown in Fig. 3 for 1992–2050, along with IEA and other data. It is clear from Fig. 3 that the IEA fuel sales data consistently indicate larger CO_2 emissions than implied by 'bottom-up' inventories. There are a number of reasons for this. Firstly, the inventories shown only estimate civil emissions; military emissions are much more difficult to estimate. Military emissions were calculated to be approximately 11% of the total in 2002 (Eyers et al., 2005), *cf.* 18% as calculated by Boeing for 1992 (Henderson et al., 1999). Secondly, the IEA data include aviation gasoline, as used by small piston-engine aircraft, but this comprised only <2% of the total in 2000. Thirdly, the inventories are idealized in terms of missions in that great circle distances are often assumed and holding patterns are not included, nor the effect of winds. Finally, some inventories are based only on

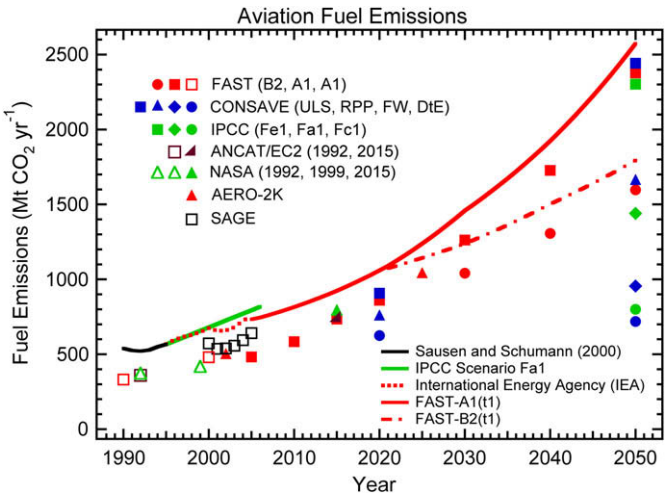

Fig. 3. Historical and present-day inventories, and future projections of civil aviation CO_2 emissions from a variety of sources: AERO2K (Eyers et al., 2005); ANCAT/EC2 (Gardner et al., 1998); CONSAVE (Berghof et al., 2005); FAST (Owen and Lee, 2006); IPCC (IPCC, 1999); NASA (Baughcum et al., 1996, 1998; Sutkus et al., 2001); SAGE (Kim et al., 2007). The open symbols indicate inventory analysis and the closed symbols indicate projections. Also shown are the CO_2 emissions implied by IEA fuel sales statistics (IEA, 2007). The IEA data represent the total of civil and military usage because all kerosene sales are included. The Sausen and Schumann (2000) data are also based on IEA. The solid (dashed) lines for FAST-A1 (B2) scenarios (evaluated with the t1 technology option) and the IPCC Fa1 scenario also account for all fuel sales in order to be consistent with the IEA values ending in 2005. In the figure legend, the FAST, CONSAVE, and IPCC symbols are shown in an order that matches the scenario labels in the parentheses in each case. The IPCC Fa1 data for 1995–2006, the IEA data and the Sausen and Schumann (2000) data are also shown in Fig. 2. Adapted from Figure 5.6 of Kahn-Ribeiro et al. (2007).

scheduled traffic, whereas others include estimates of non-scheduled traffic for the main air traffic regions. These various factors conspire to systematically underestimate aviation CO_2 emissions, an effect which has been known for some time but still remains difficult to reconcile. Thus, in RF calculations it is important to use the total kerosene fuel sales data to calculate CO_2 emissions and, thereby, reflect the total impact of all aviation activities.

3.2. Modelling methodology for 2005 and 2050 aviation radiative forcing components

The RF for aviation CO_2 is calculated explicitly, whereas other RFs are calculated either directly or indirectly from fuel data from base-year reference data from more complex models. The approach taken to calculate aviation CO_2 RF was to first calculate the CO_2 concentrations attributable to aviation using a carbon-cycle model and then calculate its RF according to a simple function as recommended by the IPCC Third Assessment Report (Ramaswamy et al., 2001). The non-CO_2 effects are scaled with fuel usage from reference values calculated with a suite of more complex models, but account for technological changes affecting emissions and other non-linear effects (e.g., contrails) as described below.

The model as described by Lim et al. (2007) is an extended version of a simplified climate model (SCM) for CO_2 and NO_x emissions effects on O_3 (Sausen and Schumann, 2000) that is also used to account for other aviation emissions and effects. The non-CO_2 effects were originally calibrated to the results from IPCC (1999) for 1992 and 2050, so that the model could be used with confidence to project forwards in time (its main purpose is to calculate temperature response, RF being an intermediate step). Having calibrated the evolution of aviation RFs over time with the IPCC (1999) results for 1992 and 2050, the model was recalibrated to a base-year of 2000 using the results of Sausen et al. (2005), which were derived from more complex models.

This scaling approach to calculate future RFs is used here in the absence of a complete and comprehensive set of RF calculations from chemical transport models, contrail coverage models and radiative transfer codes. Such a comprehensive assessment is of course preferable because of the sensitivities, for example, to regional effects and changes in climate parameters from non-aviation sources. The IPCC has accepted a similar approach (see IPCC AR4 WGI, Meehl et al., 2007) for rapid low-cost computations of future total RF and temperature response with the MAGICC model (Wigley, 2004) based on parameterizations that mimic ensemble results of more complex models (Wigley et al., 2002). Moreover, IPCC (1999) used a similar approach to scale RFs for a range of 2050 aviation scenarios from a central set of results calculated for 2050 with more complex models. Ponater et al. (2006) used a similar approach to calculate scenarios for hypothetical future liquid hydrogen (LH_2) powered fleet of aircraft, as have Grewe and Stenke (2008) to project RFs from a supersonic aviation fleet. Similarly, Fuglestvedt et al. (2008) have examined contributions of the different transportation sectors to global RF and temperature response with an SCM.

The CO_2 RF was calculated using a complete time-series of aviation fuel data as described above for the period 1940–2005. Emissions of CO_2 from fuel burn were used to calculate CO_2 atmospheric concentrations with the simple carbon-cycle model of Hasselmann et al. (1997). This model is based upon that of Maier-Reimer and Hasselmann (1987) and uses a 5-coefficient impulse response function. Such convolution integral models have their limitations when compared with more complex carbon-cycle models but they are considered to work well for small linear perturbations (Caldeira et al., 2000), such as featured in this work. Background CO_2 RFs were taken from historical data and scenario projections from the MAGICC model v4.1 (Wigley, 2004), as published in the IPCC Third Assessment Report (IPCC, 2001). The RF contribution of aviation CO_2 is then calculated using the CO_2 concentrations attributable to aviation using the simple function recommended by Ramaswamy et al. (2001), which originates from Myhre et al. (1998).

The RF reference value for O_3 increases from NO_x emissions is based upon a calibration with the ensemble results from more complex chemical transport models (CTMs) and climate chemistry models (CCMs) that provided input to Sausen et al. (2005) for 2000, adjusted by a factor of 1.15 to agree with IEA fuel burn (Prather et al., 1999). The O_3 RFs are projected forward in time using values of the NO_x emission index ($EINO_x$, g NO_x kg^{-1} fuel) from IPCC (1999). A linear relationship between O_3 RF (or O_3 burden) with increases in aircraft NO_x emissions at a global scale has been shown elsewhere to be a good approximation (e.g., IPCC, 1999 (Figure 4-3); Grewe et al., 1999; Rogers et al., 2002; Köhler et al., 2008; and also for shipping NO_x perturbations, Eyring et al., 2007) over the range of NO_x emissions used in these studies. Similarly, the reference value for the reduction in CH_4 RF from NO_x is calibrated to the results of Sausen et al. (2005) for 2000 and scaled to the changes in O_3 RF via $EINO_x$ projections. Thus far, potential non-linearities in the atmospheric chemistry of NO_x–O_3 production (e.g., Jaeglé et al., 1998) have not been clearly exhibited in global models at large scales. Non-linearities have only clearly been manifested at scales smaller than the globe (e.g. Rogers et al., 2002).

Reference values for water vapour, SO_4 and soot RFs were calibrated to Sausen et al.'s (2005) values. Future values were scaled via the respective emission indices from IPCC (1999).

The reference value for the persistent linear contrail RF was calibrated to the results of Sausen et al. (2005). The RF was projected forward on the basis of fuel usage (Sausen et al., 1998) but also incorporated an additional non-linear factor that accounts for

projected changes in propulsive efficiency (see Sausen et al., 1998), and flight route development as described by IPCC (1999). Scaling with fuel usage likely produces an upper limit value because of the requirement of certain meteorological conditions (ice-supersaturation) and saturation effects (discussed below).

The reference value for AIC RF was calibrated against the results of Stordal et al. (2005) for 2000 traffic. Projecting AIC RF forwards in time is problematic as it is unlikely that the AIC RF scales directly with fuel usage. A better physical basis for scaling both persistent linear contrails and AIC would be to use reported aircraft traffic movements (Gierens et al., 1999) and precise climatology for atmospheric conditions. For linear contrails, however, changes in the overall propulsive efficiency of the aircraft fleet needs to be accounted for in future cases (Gierens et al., 1999), for which a movements-based model (rather than fuel-based) has not currently been established. The potential AIC increase with traffic is likely to be non-linear, since a given grid cell or area of interest may saturate with AIC with additional traffic producing no extra AIC. Currently, there are no adequate physical model estimates of how various aircraft and external factors will influence future AIC. In the absence of such models, AIC is scaled with fuel usage following the approach of IPCC (1999), noting that this may produce an upper estimate of future AIC.

3.3. Updated radiative forcing estimates for aviation in 2005

The calculated aviation RFs for 2005 are given in Table 1 using the methodology outlined in Section 3.2. The table includes results for air traffic in 1992 (Prather et al., 1999) and 2000 (Sausen et al., 2005), along with fuel usage and annual emission rates of CO_2. The IPCC AR4 values from WGI and WGIII are shown as the 2000a values in Table 1.

For completeness, the 2000b values in Table 1 are included as a variant of the Sausen et al. (2005) RF values (2000a). For the 2000a values, the fuel usage for non-CO_2 RFs was calculated with a bottom-up inventory of aviation fuel. The 2000b values derive from the more complete IEA fuel estimates, which were not available at the time. Since this discrepancy was well known and IPCC (1999) also utilized a scaling factor to account for this, the 2000a non-CO_2 RFs include an upward scaling of 15%. The newly available IEA data on fuel usage (Fig. 2) shows that this uplift was too small (by about 8%) in Sausen et al.'s (2005) results. The RF for persistent linear contrails remains the same in 2000b, since contrail coverage is normalized to that of regional satellite observations. RF values for AIC were not scaled in 2000b because of their large uncertainty. The CO_2 RF presented by Sausen et al. (2005) was calculated in a slightly different way than in the present study; hence, the difference between 2000a and 2000b values. The 2005 RFs were scaled from the 2000b values rather than the 2000a values since it is consistent to use the same fuel basis in the scaling. In terms of the total RF, it makes only a small difference, of the order 1%.

The total aviation RF for 2005 is 55 mW m^{-2}, excluding AIC, which is an increase of 14% over that estimated for 2000. This exceeds the "within ±10%" range assumed by IPCC AR4 WGI (Forster et al., 2007a). The forcings that scaled linearly with fuel (i.e., water vapour, sulphate and soot aerosols) increased by 8.4% over the period 2000–2005. The RFs for O_3 and CH_4 scale somewhat differently, since a change in emission index is also expected. For contrails, the percentage increase of 18.2% is a result of not only changing fuel (the basic proxy, see Sausen et al., 1998) but also changes in propulsive efficiency and routings that result in increased contrail coverage (see IPCC, 1999, Chapter 3). Thus, the overall increase of 14% is greater than the 10% bound assumed by Forster et al. (2007a), who did not have the latest traffic and fuel data at their disposal.

The magnitude and sign of the updated 2005 aviation RF components are shown in Fig. 4 with their 90% likelihood range (see next section for uncertainty analysis), along with the values assigned by IPCC AR4. Fig. 4 also includes spatial scales of the component RFs in a format consistent with the IPCC AR4 WGI results for all anthropogenic forcings (Forster et al., 2007a) and the level of scientific understanding (LOSU) ascribed to the various forcings, which are discussed in the following section. The overall aviation RF in 2005 of 55 mW m^{-2} (excluding AIC) and 78 mW m^{-2} (including AIC) may be compared with the overall anthropogenic RFs given by the IPCC (2007), which are reproduced in Fig. 5. The aviation forcings comprise some 3.5% of total RF (excluding AIC) and 4.9% of total RF (including AIC).

3.4. Uncertainties in 2005 aviation radiative forcings

Uncertainties for aviation RFs, other than that of CO_2, are difficult to quantify. Nevertheless, it is important to understand what these uncertainties might be, in order to assess the limitations of the RF estimates and to allow for a comprehensive evaluation of aviation's contribution to climate change within a wider policy framework. Uncertainties are considered from two viewpoints; firstly the more subjective LOSU as used in IPCC analyses and secondly from a more objective viewpoint of assigning numerical uncertainties using probability distribution functions (PDFs).

Sausen et al. (2005) attributed LOSUs in a three-grade system of 'good', 'fair' and 'poor', where the aviation CO_2 RF was 'good', AIC was 'poor' and all other forcings 'fair'. Here, the updated IPCC AR4 uncertainty guidelines have been adopted, utilizing 'high',

Table 1
Historical and current-day aviation fuel usage, CO_2 annual emissions, and radiative forcings.

Year	Fuel (Tg yr^{-1})	CO_2 emission (Tg yr^{-1})	RF (mW m^{-2})[a]								
			CO_2	O_3	CH_4	H_2O	Contrails	SO_4	Soot	AIC (low, mean, high)	Total (excl. AIC)
1992 (IPCC, 1999)	160.3	505	18.0	23.0	−14.0	1.5	20.0	−3.0	3.0	0 (low) 40 (high)	48.5
2000a (Sausen et al., 2005)[b]	169.0[c]	533	25.3	21.9	−10.4	2.0	10.0	−3.5	2.5	10, 30, 80 [d]	47.8
2000b[e]	214.3	676	24.5	23.7	−11.2	2.5	10.0	−4.4	3.2	10, 30, 80	48.3
2005	232.4	733	28.0	26.3	−12.5	2.8	11.8	−4.8	3.5	11, 33, 87	55.0
% change (2005–2000b)	8.4%	8.4%	14.0%	11.1%	11.1%	8.4% [f]	18.2%	8.4% [f]	8.4% [f]		14.0%

[a] CO_2 RF depends on historical emissions and the carbon-cycle. O_3 and CH_4 values scaled to NO_x emissions, accounting for changes in $EINO_x$ over time. H_2O, SO_4, soot values scaled to fuel. Contrail values scaled to fuel but include factors that account for fleet average propulsive efficiency, aircraft size and routing.

[b] RF values are equal to the IPCC AR4 results cited by WGI and WGIII.

[c] Used for non-CO_2 perturbations and then scaled by 1.15 for inefficiencies in flight routing (see IPCC, 1999, Table 6-1, footnote (a), therein).

[d] From Stordal et al. (2005).

[e] 2000b and 2005 values are updates of 2000a values. 2000b RF values differ from 2000a because a different C-Cycle model was used and for non-CO_2 RFs, the actual global fuel consumed was greater (from IEA statistics, IEA, 2007).

[f] Deviations in the relative changes from 8.4% arising from dividing the figures of the 2005 and 2000b results are due to rounding errors.

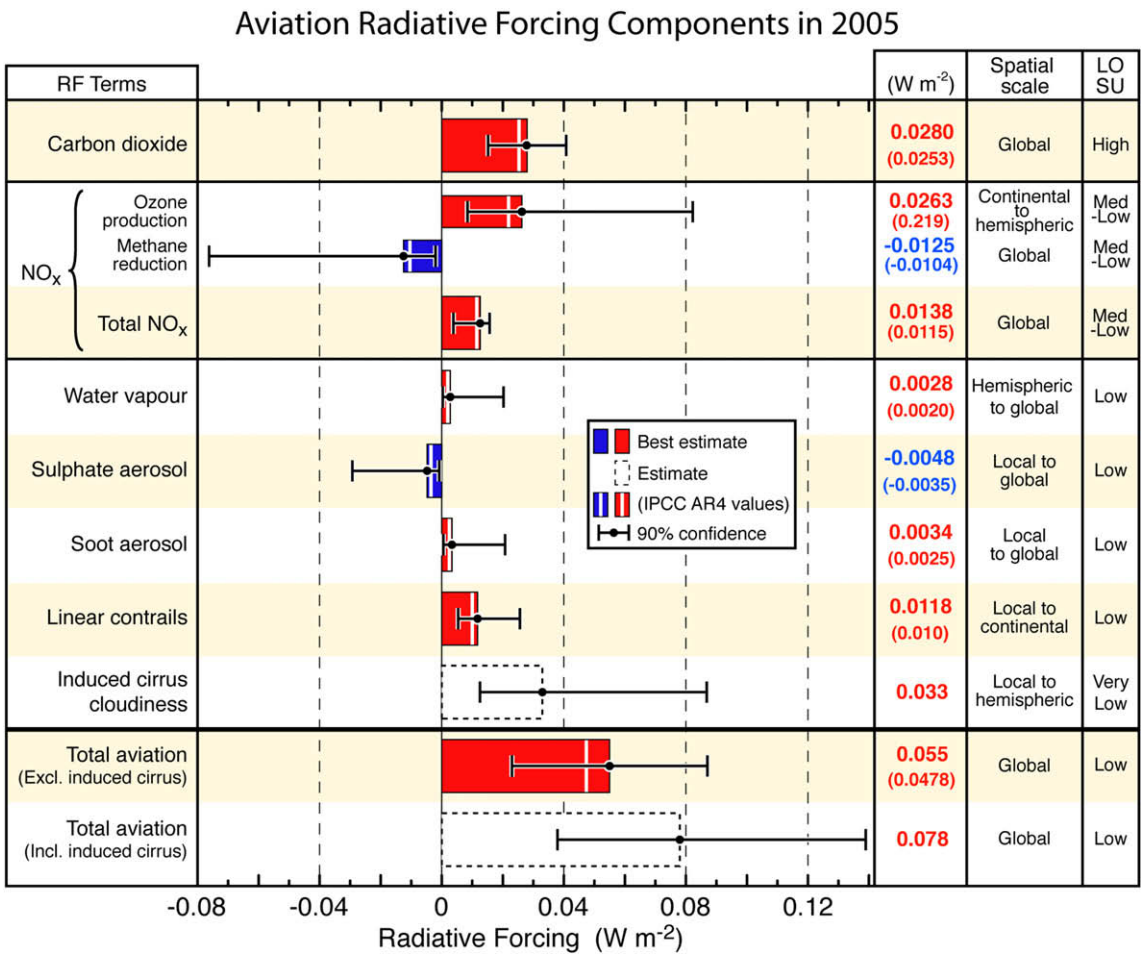

Fig. 4. Radiative forcing components from global aviation as evaluated from preindustrial times until 2005. Bars represent updated best estimates or an estimate in the case of aviation-induced cloudiness (AIC) as listed in Table 2. IPCC AR4 values are indicated by the white lines in the bars as reported by Forster et al. (2007a). The induced cloudiness (AIC) estimate includes linear contrails. Numerical values are given on the right for both IPCC AR4 (in parentheses) and updated values. Error bars represent the 90% likelihood range for each estimate (see text and Tables 2 and 3). The median value of total radiative forcing from aviation is shown with and without AIC. The median values and uncertainties for the total NO_x RF and the two total aviation RFs are calculated using a Monte Carlo simulation (see text). The Total NO_x RF is the combination of the CH_4 and O_3 RF terms, which are also shown here. The AR4 value noted for the Total NO_x term is the sum of the AR4 CH_4 and O_3 best estimates. Note that the confidence interval for 'Total NO_x' is due to the assumption that the RFs from O_3 and CH_4 are 100% correlated; however, in reality, the correlation is likely to be less than 100% but to an unknown degree (see text). The geographic spatial scale of the radiative forcing from each component and the level of scientific understanding (LOSU) are also shown on the right.

'medium', 'medium-low', 'low', and 'very low', where ranks of 'very low' are not evaluated for a range (but see below).

A LOSU of high is assigned to CO_2, consistent with Sausen et al. (2005). We depart from Sausen et al. (2005) by attributing a LOSU for O_3 and CH_4 of medium-low. This is because recent assessments of the effect of aircraft NO_x on O_3 and CH_4 forcings from a GWP emission pulse in CTMs/CCMs, or a sustained emission approach, have revealed larger discrepancies between models than might have been expected from a conventional pseudo steady-state simulation (Forster et al., 2007a; Fuglestvedt et al., in press). LOSUs of low are assigned to water vapour, sulphate aerosol, soot aerosol and contrails for a variety of reasons: most importantly, there are few assessments of water vapour, sulphate and soot RFs. Additionally for soot, the emissions index is only poorly known. For contrails, the LOSU remains low since there is a paucity of observational data of contrail coverage with which global coverage can be normalized. In addition, satellites have difficulty discriminating between visible and sub-visible contrails and assessing the optical thickness, which almost linearly affects the forcing calculation (Meerkötter et al., 1999). A LOSU of very low is assigned to AIC, which is somewhat in contradiction to the evaluation scheme set out by Forster et al. (2007a) in that a range is given here. However, this has been done since the original authors (Stordal et al., 2005) provided a range. Overall, a LOSU of low is assigned to total aviation RF, principally because of the non-CO_2 factors that represent at least 50% of the total RF.

The assessment of uncertainty within IPCC reports has become more rigorous over the years (e.g., Box TS-1 of IPCC AR4 WGI, 2007). RF uncertainties have been primarily based upon the range of values derived from different published studies, with a subjective assessment as to how much of the overall likely range is covered by available studies. The assessment of persistent linear contrails and net anthropogenic RF in Forster et al. (2007a) gave best estimates and 90% likelihoods for their RFs. Insufficient knowledge meant that it was not possible to quote a 90% likelihood range or best estimate for AIC, but rather a possible range was given, based upon Sausen et al. (2005), who adopted the values of Stordal et al. (2005). In handling uncertainties of aviation RFs, IPCC (1999) gave 67% likelihood ranges for all the RFs except AIC. For AIC there was no best estimate reported and hence no likelihood range possible.

Uncertainties used in this work are given in Tables 2 and 3 and shown in Figs. 4 and 6. The approach follows Forster et al. (2007a)

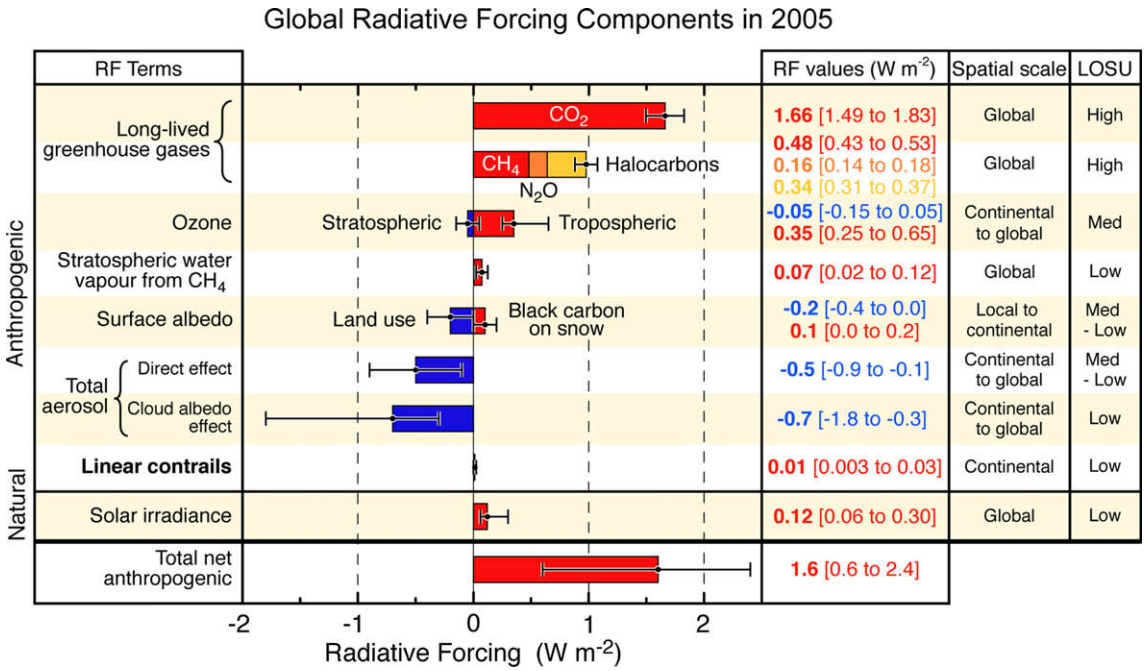

Fig. 5. Radiative forcing from anthropogenic activities and natural (solar) changes as evaluated from preindustrial times to 2005. The geographic spatial scale of the radiative forcing from each component and the level of scientific understanding (LOSU) are also shown on the right. Adapted from Figure SPM.2 of IPCC (2007).

in which normal or lognormal distributions of values for each RF component were assigned and a Monte Carlo routine used to calculate a discrete PDF for the net anthropogenic radiative forcing. This approach to uncertainties is similar to that outlined by Boucher and Haywood (2001). The assigned uncertainties are associated with the model evaluation of each component forcing and do not include uncertainties in the underlying fuel usage. The median values and 90% likelihood ranges (high/low) of the assumed distributions for each aviation RF component and for the Monte Carlo PDFs are given in Table 2. The distribution widths for linear contrails, AIC and non-aviation (total anthropogenic CO_2) forcings are based on AR4 values. For the other aviation RFs, widths used in the IPCC (1999) report were adopted with the exception of water vapour. The minimum water vapour RF of zero given by IPCC (1999) would not be possible to represent within a lognormal distribution framework; therefore a near-zero minimum forcing was chosen to provide a lognormal distribution (see Table 2). The fractional RF values make use of the PDF of net anthropogenic RF from Figure 2.20b of Forster et al. (2007a) (note that this excludes AIC but includes linear contrails).

Monte Carlo samplings (one-million random points) of the PDFs were used to combine uncertainties in order to estimate both the total RF from aviation, its fractional contribution to the total anthropogenic RF, and the 90% likelihood ranges associated with each value. The different RF terms are assumed to be independent (uncorrelated) except those of O_3 and CH_4, as discussed below. The results are given in Table 3 and shown in Figs. 4 and 6. The uncertainties expressed as 90% likelihood ranges are consistent with the IPCC (2007) approach. In IPCC language (see Technical Summary; IPCC, 2007) the RF is "very likely" to be within this quoted range.

The model estimates of the O_3 and CH_4 RF uncertainties are assumed to be linked and compensatory (*i.e.*, if the O_3 RF is more positive than expected, the CH_4 RF would be more negative than expected). This is justified because the CH_4 change is directly influenced by the earlier O_3 change. As an intermediate step in combining uncertainties, the O_3 and CH_4 RF terms were combined to form a 'Total NO_x' term with a separate Monte Carlo sampling. The Total NO_x term in Table 2 and Fig. 4 has a median value of 12.6 mW m^{-2} with a 90% confidence range of 3.8–15.7 mW m^{-2} and is considered a best estimate for the Total NO_x RF. While the median value is close to the difference between the O_3 and CH_4 best estimates, the likelihood range is significantly smaller than either the O_3 or CH_4 range. In this case the Monte Carlo sampling assumed 100% correlation between the terms. IPCC (1999) notes that the uncertainties of these terms are highly correlated. If the correlation is reduced to 50% (0%), the median values changes only slightly to 12.5 (11.6) mW m^{-2} whilst the likelihood range increases to −28 to

Table 2
Best estimates and high/low limits of the 90% likelihood ranges for aviation RF components derived in this paper and for the total CO_2 RF and net anthropogenic RF from Forster et al. (2007a).

Aviation RFs										Anthropogenic RFs	
RF (mW m^{-2})	CO_2	O_3	CH_4	Total NO_x (O_3 + CH_4)	H_2O	Contrails	SO_4	Soot	AIC	Total CO_2	Total (excl. AIC)
2005 best estimate[a]	28.0	26.3	−12.5	12.6	2.8	11.8	−4.8	3.4	33	1660	1600
2005 low	15.2	8.4	−2.1	3.8	0.39	5.4	−0.79	0.56	12.5	1490	600
2005 high	40.8	82.3	−76.2	15.7	20.3	25.6	29.3	20.7	86.7	1830	2400
Distribution type	Normal	Lognorm.	Lognorm.	Discrete pdf	Lognorm.	Lognorm.	Lognorm.	Lognorm.	Lognorm.	Normal	Discrete PDF

Notes: Estimates of aviation uncertainty based on IPCC (1999) except for linear contrails and AIC which employ uncertainty estimates from IPCC AR4 WGI (2007). Note that IPCC (1999) used 67% uncertainty ranges compared to the 90% likelihood ranges used here. Non-aviation RFs and their uncertainty are taken directly from Forster et al. (2007a).
[a] Values from Table 1.

Table 3
Aviation non-CO_2 and total aviation RFs and their fraction of total anthropogenic RFs.

	Aviation non-CO_2 RF (mW m^{-2})		Total aviation RF (mW m^{-2})		Total aviation RF as percentage of total anthropogenic RF		
	No AIC	With AIC	No AIC	With AIC	CO_2 only	No AIC	With AIC
2005 median	27	49	55	78	1.6%	3.5%	4.9%
2005 low	−2.6	13	23	38	0.8%	1.3%	2.0%
2005 high	57	110	87	139	2.3%	10%	14%

Notes: Results for PDFs derived from a Monte Carlo model (see text for details). High/low values give 90% likelihood range.

49 (−49 to 67) mW m^{-2}. The Total NO_x value was combined with the other independent RF terms in the Monte Carlo samplings to calculate the total and fractional aviation RF values in Table 3 and Figs. 4 and 6. It is important to acknowledge that the O_3 and CH_4 forcings underlying the Total NO_x forcing term do not balance each other out on local scales and hence some features of the climate impact of NO_x emissions cannot be derived from only the global mean Total NO_x forcing.

The 100% correlation of the O_3 and CH_4 RF terms assumed here may not be fully justified. For example, some errors in the radiative forcing calculation of O_3 would be roughly independent of those in CH_4 radiative forcing. A correlation of less than 100% increases the uncertainty in the total aviation RF derived here as noted above. However, the estimated uncertainties in the underlying O_3 and CH_4 RF terms are likely to be overestimates because they have not been updated from IPPC (1999) and hence do not reflect the increased skill of contemporary CTMs and CCMs (e.g., Fiore et al., 2008; Stevenson et al., 2006). Thus, a 100% correlation is a reasonable compromise until a new multi-model evaluation of the response to aviation NO_x emissions is undertaken. We also note that in calculations of the response to aviation NO_x, the O_3 RF increase and CH_4 RF decrease cancel to a large extent in the global mean, but do not cancel geographically because their the regional RF patterns are very different (cf. Prather et al., 1999, their Figs. 6-9). The RF from O_3 is concentrated in the Northern Hemisphere while the RF from CH_4 exhibits a more homogeneous pattern (similar to that of CO_2) because of their differing lifetimes.

The RF estimate of AIC includes a component due to linear contrails (Forster et al., 2007a). As a consequence, when AIC is included in the total aviation RF, linear contrails are not separately added. Note also that the net anthropogenic RF from Figure 2.20b of Forster et al. (2007a) does not include AIC. Hence, AIC is added (and linear contrails removed) to the Monte Carlo model of net anthropogenic RF when fractions are calculated in the present study.

An implicit assumption in the use of the Monte Carlo model here is that uncertainties in the RF terms other than NO_x and O_3 are entirely independent. However, the short-lived non-cloud forcings from aerosol species and water vapour are likely to exhibit a degree of correlation and modelling studies typically employ similar relationships between their emissions of forcing precursors. Accounting for these additional correlations is likely to reduce the overall uncertainty range. However, the degree of correlation is difficult to estimate as these RFs are so dependent on the location of their emission source and this dependence is largely species specific. We therefore chose to ignore this compensatory effect in our analyses but acknowledge that our uncertainty ranges could be overly large because of this omission.

Table 3 and Fig. 6 provide separate RF results for the CO_2 and non-CO_2 terms along with total aviation for several cases and results for the aviation total as a fraction of total anthropogenic RF. Fig. 4 shows a summary of the RF best estimates for each component except AIC, the median values of the PDFs for the totals with and without AIC, and error bars in each case denoting the 90% likelihood range. The total RF from aviation in 2005 excluding AIC is 55 mW m^{-2} and very likely (90% likelihood) to be within the range of 23–87 mW m^{-2}. Including AIC increases the total to 78 mW m^{-2} and the very likely (90% likelihood) range to 38–139 mW m^{-2}. The larger range results from the larger likelihood range for the AIC RF.

As a fractional contribution, aviation CO_2 RF is responsible for 1.6% (0.8–2.3%, 90% likelihood range) of the total global anthropogenic CO_2 RF in 2005. With AIC excluded, the net RF from aviation is responsible for 3.5% (2–10%, 90% likelihood range) of the total anthropogenic RF. Including AIC increases the net RF from aviation to 4.9% (2–14%, 90% likelihood range) of the total anthropogenic RF. Thus, an aviation contribution larger than 14% is very unlikely (less than 5% probable).

Fig. 6 shows the PDFs for the aviation RF for CO_2 alone, the group of non-CO_2 terms and the total along with the PDF of the contribution of aviation CO_2 and total aviation RF as a percentage of total anthropogenic forcing. These analyses have been performed including (upper two panels, A, B) and excluding (middle two panels, C, D) the AIC contribution. The lower-most panel (E) shows the PDF of total anthropogenic RF with and without AIC that is used in the Monte Carlo calculations. Typically, the CO_2 components have a narrow distribution, reflecting the smaller uncertainties. The non-CO_2 components (excluding AIC) have a broader distribution, reflecting the larger uncertainties which dominate the shape of the total PDF (see panel A). When AIC is also combined with the other non-CO_2 PDFs, a much broader range results in the total aviation RF. The total anthropogenic PDF has a much broader distribution than any of the aviation PDFs, which is a result of the larger inherent uncertainties, arising mostly from the direct and indirect aerosol effects (see Forster et al., 2007a).

An additional uncertainty that is omitted in this study, but one that could be added to the results in Tables 2 and 3 and Fig. 6, is that associated with emission scenarios. Uncertainty in the historical fuel usage affects all the RF components reported here because CO_2 concentrations are directly derived from fuel use and other terms are scaled to fuel use. The uncertainty would not apply uniformly because CO_2 forcing depends more strongly on historical emissions because of its long atmospheric lifetime, whereas the non-CO_2 components have shorter lifetimes and hence depend upon current fuel use rates. In addition, contrail and cloud forcings might not scale uniformly with fuel use uncertainty if, for example, the uncertainties had regional dependencies.

4. Aviation climate forcings: 2050 projections

4.1. Aviation emissions projections up to 2050

Whilst the 2005 aviation RF is relatively modest (3.5% of the total anthropogenic forcing, excluding AIC), the projected strong growth in traffic will result in larger future forcings unless the emissions from the fleet are reduced. Forecasts from ICAO and industry (FESG, 1998; Airbus, 2007) suggest traffic growth (RPK) rates of the order 4.5–6% yr^{-1} over the next 20 years or so, such that passenger traffic is expected to double every 15 years. Future projections are generally categorized as either a forecast at around 2020–2025 that generally assumes some likely extrapolation of traffic and technology, or as a scenario for 2050 requiring some plausible traffic and technology projections.

Global aviation emissions of CO_2 were previously calculated by the Forecasting and Economic Support Group (FESG) of ICAO for the IPCC Special Report (1999) by using forecasts of traffic and emissions to 2015 from a base year of 1992 and thereafter by applying a model of the relationship between global RPK and global GDP (which exhibit a strong relationship at this level of aggregation) to

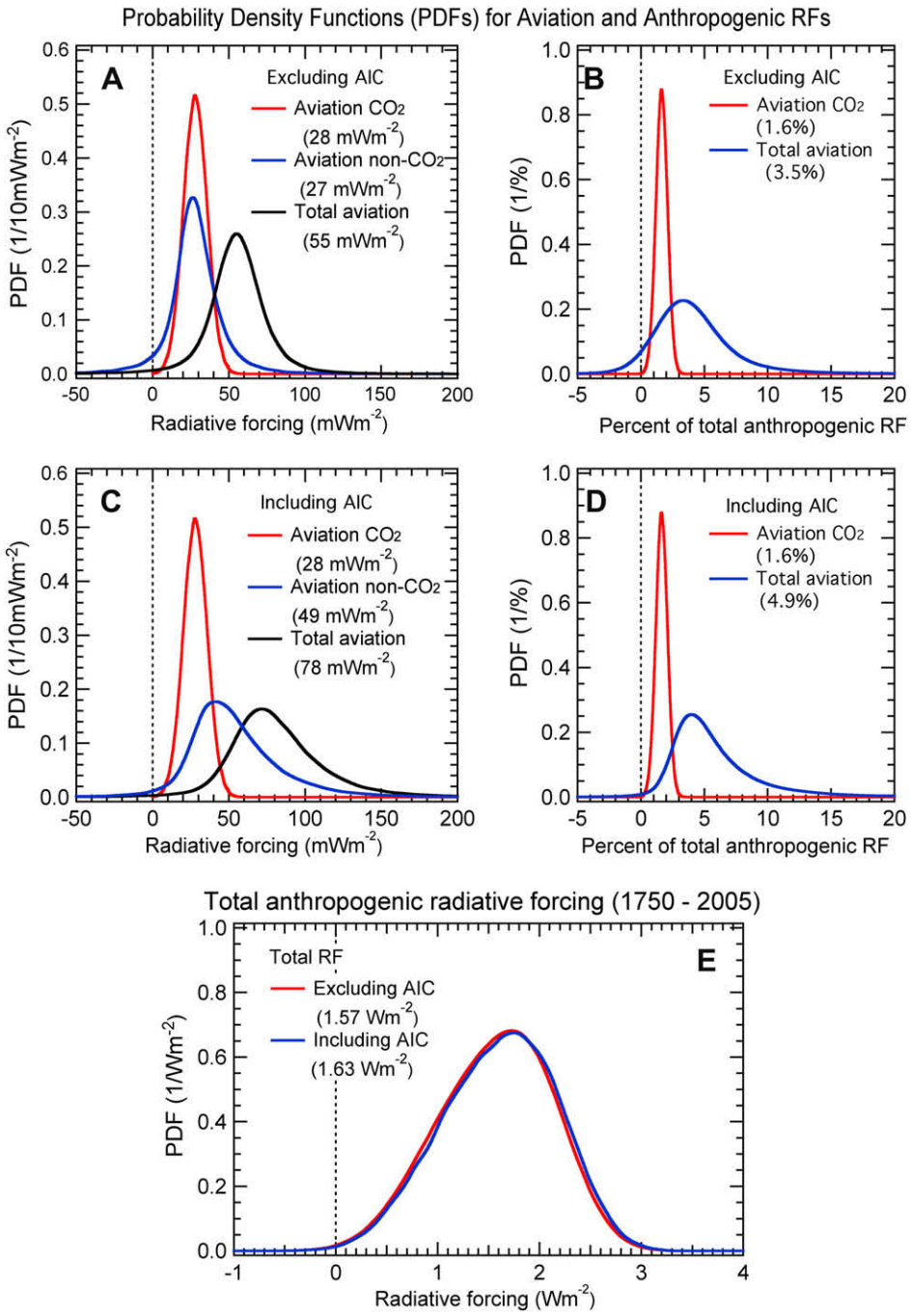

Fig. 6. Probability distribution functions (PDFs) for aviation and total anthropogenic radiative forcings (RFs) based on the results in Tables 2 and 3. All aviation RFs are from the updated 2005 emission values derived in this study. Uncertainties are expressed by a distribution about the best-estimate value that is normal for CO_2 and lognormal for all other components. A one-million point Monte Carlo simulation run was used to calculate all PDFs. PDFs of aviation RFs excluding (including) aviation-induced cloudiness (AIC) are shown in Panels A and B (C and D). Panels A and C: PDFs for aviation CO_2 and sum of non-CO_2 RF components, and the total aviation RF. Panels B and D: aviation CO_2 and total aviation RFs as a percentage of the total anthropogenic RF (Panel E). Each PDF is normalized to unity over the interval noted in parentheses in the vertical axis label. The numbers in parentheses in each panel legend are the median values of the corresponding PDFs. See text for further details.

extrapolate trends, in this case to 2050. If an independent projection of GDP data is available, a model of the historical relationship allows an extrapolation of future global RPK estimates. Previously, the FESG (1998) used GDP data from the IPCC IS92 scenarios; specifically, IS92a, IS92c, and IS92e, representing mid, low and high growth rates, respectively (Henderson et al., 1999). These scenario results for civil aviation emissions in 2050 ranged from 800 Tg CO_2 yr^{-1} (low 'Fc') through 1440 Tg CO_2 yr^{-1} (mid 'Fa') to 2302 (high 'Fe') Tg CO_2 yr^{-1} (Fig. 3).

For the present study, future emissions were calculated with a sophisticated global aviation inventory model, FAST (Lee et al., 2005), by using external data for RPK and GDP projections to 2050 (Owen and Lee, 2006). Each aircraft type in the FAST model is defined by seat-capacity banding, so that RPK data could be used to determine the necessary size of the global fleet and its subsequent emissions by incorporating future projections of fuel efficiency. The approach accounted for projected changes in technology using a 'traffic efficiency' concept (*i.e.*, RPK kg^{-1} fuel (Henderson et al.,

1999)) that relates emissions to RPK for different aircraft types and allows aggregation at the fleet level. The approach allowed the modelling of the improvements from incorporating more fuel-efficient aircraft into the fleet. Regional forecasts of RPK to 2020 were used from ICAO/FESG to calculate emissions in 2005, 2010, 2015, and 2020. After 2020, global RPK projections to 2050 were calculated using a non-linear Verhulst function with the IPCC Special Report on Emissions Scenarios (SRES) global domestic product (GDP) projections, A1 and B2 (IPCC, 2000), to calculate emissions for 2030, 2040, and 2050 in a similar manner to Henderson et al. (1999). These SRES scenarios, designated here as FAST-A1 and FAST-B2, were chosen because they were the 'baselines' against which assessments of mitigation were undertaken by the IPCC within WGIII for AR4. The overall growth of aviation in scenario B2 is not greatly dissimilar to that of the mid-range IPCC (1999) scenario, Fa1, and the A1 scenario is likewise similar to the upper-range IPCC (1999) scenario, Fe1. The FAST-A1 and FAST-B2 results are shown in Fig. 3 along with other earlier projections. The FAST-A1 and FAST-B2 scenarios include a scaling by a fixed amount of 64 Tg fuel yr^{-1}, respectively, in order to be consistent with IEA fuel sales data up to 2005 (Fig. 3). This amount represents the average difference between 1990 and 2000 data from a bottom-up inventory of aviation emissions (Lee et al., 2005), excluding military emissions and IAE data on fuel sales data.

The FAST-A1 and FAST-B2 scenarios are further differentiated by two technology factors ('t1' and 't2') that refer to different assumptions of future NO_x emissions, as previously described by IPCC (1999). The technology1 (t1) assumption, a base case, is that advances in airframe and engine technology will be typical and market-driven. The technology2 (t2) assumption is that more emphasis will be placed on reducing NO_x levels to the slight detriment of CO_2 emission levels (see Henderson et al. (1999) for details). However, for the results presented here, the aviation forcings have been calculated against the relevant overall background scenarios, in contrast to the IPCC (1999) which calculated aviation-oriented variants (IS92a, c, e) against the same background scenario (IS92a).

4.2. Aviation radiative forcing estimates for 2050

The RF estimates for 2020 and 2050 scenarios are given in Table 4 and shown in Fig. 7. The future best estimates are derived from 2005 values given in Tables 1 and 2 using the scaling methodology described in Section 3.2. No best estimates are available for future AIC because of the LOSU of 'very low' in 2005. This is indicated in Fig. 7 with dashed lines displaying the scaled AIC values. Atmospheric models are not able to calculate AIC effects because constraints on the physical processes involved are poorly known. Instead, the AIC values given in Table 4 are linearly scaled to fuel usage using the 2005 value as a reference in the absence of a more suitable metric, as was done similarly by Prather et al. (1999). However, it is likely that increases in AIC RF with additional air traffic in a given region saturate at some threshold level of additional cloud cover. There is currently no means by which this threshold can be inferred or calculated. Thus, linear scaling produces AIC RF values that are likely to represent the upper limits of those that would actually occur.

The increased traffic projected by 2020 and 2050 results in increased emissions and RF, despite the assumed technological improvements in the fleet. This is an expected result, consistent with IPCC (1999), since technological improvements tend to enter the fleet at a rate driven by its slow turnover of aircraft, a consequence of their long utilization lifetimes, which are of the order 25 years. In 2020, only one estimate of RF is given, since this is based upon an ICAO fleet forecast (rather than a scenario). In this case, the RF total is 84 mW m^{-2} (excluding AIC), a factor of 1.75 greater than in 2000 (or 1.5 × 2005 RF). For 2050, two main SRES storyline scenarios have been followed; A1 and B2, with two technology variants (t1, t2), one of which emphasizes NO_x reduction to the detriment of CO_2 emissions (see IPCC, 1999, Chapters 7 and 9). The total RF for these scenarios is in the range 183–194 mW m^{-2} (A1/t2 − A1/t1) and 146–154 mW m^{-2} (B2/t2 − B2/t1), which are factors of approximately 4 and 3 times greater than total aviation RF in 2000.

The 2050 aviation RF estimates are scaled from total fuel scenarios. Similarly, IPCC (1999) scaled a range of 2050 scenario results from two core results with geographical patterns of emissions. The error introduced into the IPCC (1999) results was of the order ~9% based on a comparison of the results from the two gridded scenarios with linear scaling. Such geographical variation has not yet been estimated for our future scenarios, the subject of ongoing work. These estimates of 2050 aviation RFs also ignore the effects of climate change, e.g. changed water vapour or temperatures. Assessment of the impacts of e.g. water vapour on OH concentrations (*e.g.*, Johnson et al., 1999) and temperature/water vapour on contrail formation (*e.g.*, Marquart et al., 2003) is limited and more extensive and detailed work would be required to include such factors. The available studies indicate that increased water vapour and temperatures would tend to decrease the estimated impacts.

We note that there are uncertainties introduced into the 2050 RF values by the methodologies employed, described in detail in Section 3.2, since we have used simplified methods to reproduce results from more complex process-based models for linear contrails and NO_x-induced O_3 and CH_4 RF perturbations. In the case

Table 4
Aviation fuel usage, CO_2 emissions and RFs for 2020 and 2050.

Year/study [a]	Fuel ($Tg\ yr^{-1}$)	CO_2 emission ($Tg\ yr^{-1}$)	RF ($mW\ m^{-2}$)									Percentage Contribution to total RF (excl. AIC)[c]
			CO_2	O_3	CH_4	H_2O	Contrails	SO_4	soot	AIC [b] (low, mean high)	Total (excl. AIC)	
2020	336.0	1060	40.8	40.6	−19.2	4.0	20.2	−7.0	5.0	16, 47, 125	84.4	
2050 A1t1	816.0	2573	76.3	109.8	−52.0	9.7	55.4	−16.9	12.1	38, 114, 305	194.4	4.7 (3.4–5.2)
2050 A1t2	844.9	2665	77.7	85.3	−40.4	10.0	55.4	−17.5	12.5	39, 118, 315	183.0	4.4 (3.2–4.9)
2050 B2t1	568.8	1794	73.3	76.5	−36.3	6.7	37.2	−11.8	8.4	27, 80, 212	154.2	4.2 (3.7–4.2)
2050 B2t2	588.9	1857	74.5	59.4	−28.2	7.0	37.2	−12.2	8.7	27, 82, 220	146.5	4.0 (3.5–4.0)

[a] All projections and scenarios are based on (Owen and Lee, 2006), see also (Kahn-Ribeiro et al., 2007), which account for ICAO predictions of the global fleet to 2020 in terms of number of aircraft and size, and then use methods similar to Henderson et al. (1999) to project RPK to 2050, which includes projected changes in fleet fuel efficiency and tradeoffs between NO_x and CO_2 emissions for more aggressive NO_x reduction scenarios. The nomenclature 'A1' and 'B2' refers to consistency with two of the IPCC SRES GDP projections and 't1' and 't2' refer to two levels of NO_x technology as described by Henderson et al. (1999). Results are also shown in Fig. 7.

[b] AIC is scaled to fuel usage in the absence of a more suitable metric, as was done similarly by IPCC (1999). However, it is likely that saturation effects occur with additional cloud cover but there are currently no means by which the threshold for this can be determined or calibrated.

[c] Note that totals in all cases exclude AIC. The ranges given here are not PDFs but rather ranges based on different SRES scenario variants from different models. Background total RFs were derived from MAGICC v4.1 (Wigley, 2004). The percentage contributions given are for illustrative or marker scenarios of SRES (here, A1B-AIM; B2-Message). The range in brackets was derived using other emissions according to the main 'families' of SRES scenarios (here, A1B-AIM, A1-ASF, A1-Image, A1-Message, A1-MiniCAM, A1T-AIM, A1T-Message, A1F1-MiniCAM and; B2-Message, B2-AIM, B2-ASF, B2-Image, B2-MiniCAM, B2Hi-MiniCAM).

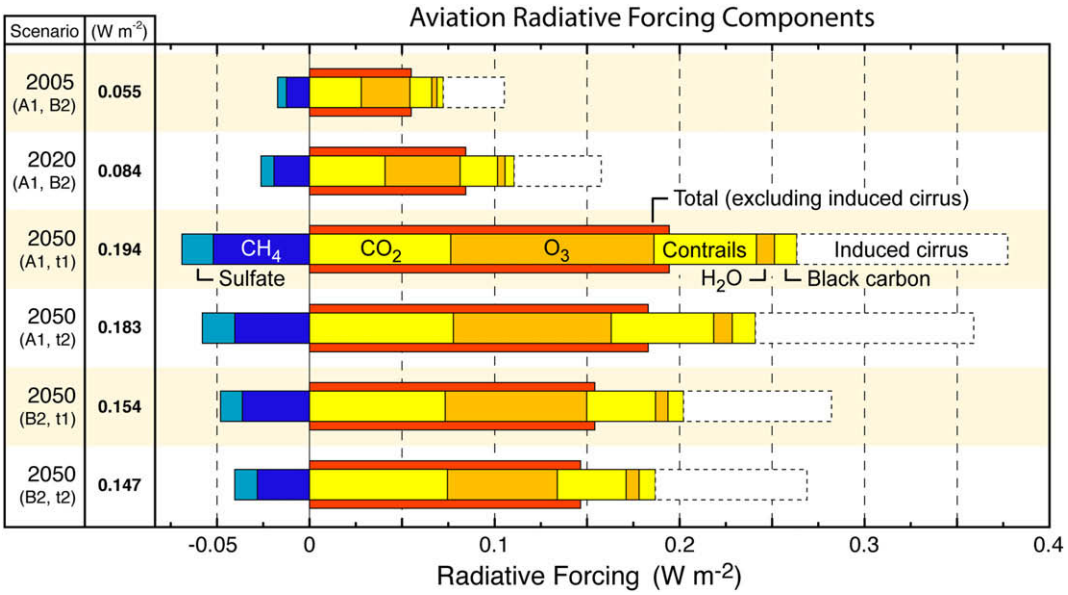

Fig. 7. Aviation RF components for 2005, 2020 forecast and 2050 scenarios A1(t1), A1(t2), B1(t1), and B1(t2) as listed in Table 4. The total aviation RFs as shown by the red bars and numerically on the left do not include estimated induced-cirrus (AIC) RFs.

of CO_2 RF, we have employed a state-of-the-art methodology; for AIC, no process-based model currently exists that is described in the literature. A complete assessment of future aviation effects that encompasses a suite and ensemble of appropriate process-based models is preferable but would require an international effort on the scale of an IPCC assessment or similar large-scale project.

5. Mitigation technologies and strategies

The AR4 WGIII report addressed a number of issues relating to transport, including aviation: its current status and future trends, mitigation technologies and strategies, the mitigation potential until 2030, and policies and measures. The interest in mitigation of aviation climate forcing will continue to grow in response to increasing confidence in the projections of significant anthropogenic climate change. The primary focus of IPCC AR4 WGIII's evaluation of emissions and mitigation potential was with respect to CO_2, but non-CO_2 effects were clearly identified as being important.

5.1. Mitigation technologies and strategies

Improving the fuel efficiency of aircraft is a major area of technological research and development, since it directly improves airlines' direct operating costs. Technological improvements usually involve aerodynamic changes, weight reductions, more fuel-efficient engines, and increased operational efficiency. Currently, no fuel-efficiency standards have been adopted within the industry.

Improving engine fuel efficiency through design changes requires testing to ensure compliance with safety and reliability requirements. Moreover, tradeoffs between noise and emissions (NO_x, HCs, CO, soot) performance also need to be considered. Engineering and environmental performance tradeoffs often impose constraints on the improvements being sought. Fuel efficiency can be improved through the use of higher pressure ratios in engines, although this development route can increase combustor temperatures and push material design limits beyond current thermal capabilities and impact upon other emissions (principally NO_x but also soot), which imposes design and performance challenges. Other developments, such as gearing the drive to the engine fan (from which most of the engine's thrust is derived) to optimize its speed differently from its driving turbine, may also assist emissions reductions in the future.

Whilst fuel efficiency of jet aircraft has been estimated to be improved by more than 60% over the past 40 years (i.e., since the introduction of the Boeing B707-120 aircraft) in terms of emissions of CO_2 per passenger km (IPCC, 1999), many of these improvements have come from step changes in technology (e.g., turbojet-to-first-generation turbofan engines such as those on B707/B727 and B747-100 aircraft and first-to-second-generation turbofans, e.g. those on B777 aircraft and its variants). Some efficiency gains have also come about through improved airframe aerodynamics and material changes that have reduced weight. In the near term, it is envisaged that most of the further improvements will be brought about through increased usage of lightweight materials. In the longer-term, IPCC AR4 WGIII considered that more radical designs such as blended wing body and unducted-propfan engine aircraft (a large open-rotor blade) would be required to realise further step-change improvements (Kahn-Ribeiro et al., 2007).

Alternative fuels to kerosene may offer some advantages in the longer-term. In terms of non-C fuels, it seems that liquid hydrogen (LH_2) is the only real alternative in prospect. Usage of LH_2 would require much larger airframe storage capacity, which would add weight and drag to conventional airframes. Critically, the production of the LH_2 fuel would need to be carbon-neutral (i.e., energy from renewable resources) in order for it to offer real advantages over kerosene in mitigating and minimizing the future climate impacts of aviation operations. There is consensus that development of such technologies is at least a decade or more away and most likely will only be pursued if there is a more general move to a hydrogen-based fuel economy. Hydrogen powered aircraft would produce more contrails than kerosene-powered aircraft because of increased water vapour emissions, which could potentially produce contrails that have a smaller optical depth than conventional contrails. Therefore, the benefit in terms of total RF of using LH_2 fuel would only become apparent a few decades after introduction of this alternative fuel (Marquart et al., 2001; Ponater et al., 2006).

Biofuels may also offer some advantages if they can be developed economically and in compliance with the exacting performance and

safety standards that are required for civil aviation (Daggett et al., 2008). However, there are fundamental questions of the economic and ecological viability of producing significant quantities of biofuels, which are likely to find more practical uptake and usage in other transport sectors (Kahn-Ribeiro et al., 2007). In addition, there are increasing concerns over land-usage conflicts between food and fuel production in developing nations (Wardle, 2003).

Air traffic management and different operational practices hold some prospect for reductions in fuel usage or mitigation of environmental effects of aviation. The most obvious reductions in fuel usage might come about from an improved air traffic management system that would better optimize cruise altitudes through reduced vertical separation minimum (RVSM) and reduced delays and holding patterns on arrival. A EUROCONTROL study (Jelinek et al., 2002) showed that the introduction of RVSM over Europe might result in a reduction in fuel burn and CO_2 emissions of 1.6–2.3% over the prior conditions. However, it should be stressed that optimizing the air traffic management system is a one-off saving and not one that could be incrementally further improved upon.

Non-CO_2 effects may also be reduced by changing cruise altitudes. Parametric modelling studies (Fichter et al., 2005; Grewe et al., 2002; Gauss et al., 2006) indicate that effects from contrails and O_3 can generally be reduced by lowering overall cruise altitudes. These studies did not propose implementing blanket reductions in cruise altitudes on a global basis but rather simply tested the hypothesis of a reduced effect via a parametric study. Mannstein et al. (2005) suggested that only minor tactical changes of altitude would be necessary on real flights to avoid ice-supersaturated regions, should suitable data become available on this parameter that would allow flight-by-flight prediction of contrail formation. However, their analysis was based on only one region with the majority of layers being ~510 m (with a standard deviation of 600 m) – in many regions cirrus clouds form over layers 1–2 km think, so that generalizations in the absence of better statistics of supersaturated regions are premature. However, there are tradeoffs that need to be considered in that reductions in cruise altitudes would incur a fuel burn penalty which is not straightforward to quantify, since the RF effects of CO_2 emitted on a particular flight are longer lasting than those of a contrail formed during the same flight (Wit et al., 2005; Forster et al., 2006, 2007b).

Lowering flight speeds could also yield significant fuel savings if engines and airframes were re-designed to realise such benefits (such benefits could not be realised by lowering speeds of current aircraft). The technology for this already exists and unducted-propfan engines that are more fuel efficient than turbofan engines at the lower speed to which they are limited could be developed further. However, there are disadvantages in terms of increased noise and possibly decreased passenger comfort as cruise altitudes would be reduced over those currently employed for conventional jet-engine aircraft.

5.2. Mitigation potential

IPCC AR4 WGIII (Kahn-Ribeiro et al., 2007) examined the mitigation potential that might be possible by 2030. Five cases were examined using the ICAO-FESG fleet forecast (ICAO/FESG, 2003) to project future growth and composition including:

1. growth but no technology change;
2. technology changes at 2005 to be 'best available technology' and specific Airbus A380 and Boeing B787 technologies;
3. an overall fleet fuel-efficiency improvement of 1.3% yr^{-1} to 2010, 1% yr^{-1} to 2020 and 0.5% yr^{-1} thereafter based upon Greene (1992) – this was assumed to be a reference case;
4. an advanced technology case brought about by regulatory pressures that yielded a further 0.5% yr^{-1} fuel efficiency from 2005 on derived from cost estimates (43); and lastly,
5. a case similar to (4) but yielding a further 1% fuel efficiency per year from 2005 on.

The percentage changes estimated in global emissions of CO_2 in 2030 over the reference (case 3) were: increases of 29% and 11.9% (cases 1 and 2) and decreases of 11.8 and 22.2% (cases 4 and 5). For all cases, CO_2 emissions increase in 2030 over 2002 levels by factors ranging from 3.29 (case 1) down to 1.98 (case 5).

It is important to note that the above analysis is somewhat rudimentary and not fully self consistent since the fuel efficiency trend of 1.3% yr^{-1} in the reference case (3) of Greene (1992) already assumes changes in fleet composition (i.e., aircraft size) and introduction of advanced technologies post 2000 such as blended wing body aircraft, laminar flow control and unducted propfans. Clearly, more work needs to be done on the historical gains in fuel efficiency and how this might be realistically projected forward but the IPCC (1999) study suggests indicative values. A significant factor in limiting CO_2 growth from aviation over the past 15 years or so has been load factor, which has increased from 68% (1989) to 76% (2006) as a global average (see Fig. 8).

In all the above cases studied, it is envisaged that demand-driven growth of civil aviation will outstrip fuel-efficiency improvements, from all sources, as was also made clear by IPCC (1999).

5.3. Policies and measures

The mitigation policies and measures considered by IPCC AR4 WGIII (Kahn-Ribeiro et al., 2007) across the range of transport modes included:

- land use and transport planning;
- taxation and pricing;
- regulatory and operational instruments;
- fuel economy standards;
- transport demand management;
- non-climate policies that influence greenhouse gas emissions;
- co-benefits and ancillary measures.

For aviation, economic instruments have been the main policy-measures that have been considered. Kerosene taxation remains an

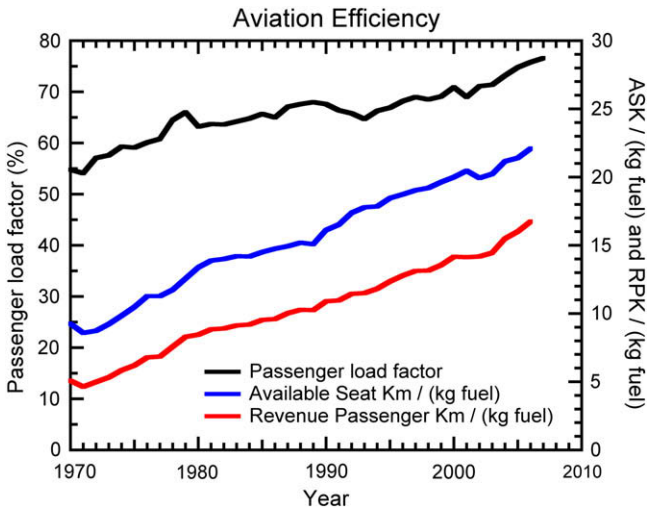

Fig. 8. Aviation efficiency data for 1970–2007: passenger load factor (%) (left hand axis) and RPK and ASK per unit fuel burn (right hand axis), source ICAO.

unpopular measure for the aviation industry and its prospect has caused some disagreement between some ICAO Member States, although the European Union (the EU) regards taxation as a viable mitigation option. It is considered likely that an introduction of taxation at a regional level would bring about competitive distortions (Resource Analysis, 1999), although some states impose local taxation on fuel but use the revenues for aviation infrastructure developments. Others have examined the potential impacts of an en route emissions charge (Wit and Dings, 2002) and concluded that if it were applied in a non-discriminatory manner that it would not make a significant impact on competition between European and non-European carriers. Most studies of this type on taxation or charges conclude that emissions savings are made from reductions in demand. This contrasts with a study for ICAO-CAEP on the impact of an open emission trading system that found that demand was reduced by only 1% over a base case.

Since Article 2.2. of the Kyoto Protocol specifies that 'reducing or limiting emissions' of CO_2 from aviation should be done through ICAO, market-based options have been discussed within that forum. However, consensus at the global level through ICAO on the introduction or use of economic instruments has not been reached thus far. As a result, the European Commission (EC) has embarked upon the development of a climate policy for CO_2 – emissions trading – that includes international aviation. The EC presented proposals in 2006 on the development of an emissions trading scheme that will bring aviation within the existing trading scheme within Europe. This proposal was controversially discussed between the EC, the European Parliament and the European Council, and in 2008, resulted in a compromise, according to which all flights within the EU and all flights to/from European airports will be covered from 2012 onwards, and the emissions will be capped at average levels over the period 2004–2006. A model analysis projects an emissions reduction of 46% over a base case by 2020, mainly through the purchase of allowances from other sectors and emissions savings made elsewhere (EC, 2006). Recently, at the General Assembly of ICAO in September, 2007, market-based options for controlling emissions of aviation CO_2 were discussed. ICAO has endorsed the concept of an open, voluntary emission trading system but has not initiated such a system. In response to the proposal of the European Commission to include non-European carriers arriving or departing at European airports into the European Emissions Trading Scheme, the 2007 General Assembly of ICAO urged Member States not to apply an emissions trading system on another state's airlines "except on the basis of mutual agreement between those States". In response to this Assembly Resolution, all 42 European Member States of ICAO entered a formal reservation and stated that they did not intend to be bound by it (ICAO, 2007).

6. Discussion

6.1. Aviation fuel consumption and CO_2 emissions in context

Emissions of CO_2 from aviation represented 2.5% of total fossil fuel emissions of CO_2 in 2005, using statistics from the Carbon Dioxide Information Analysis Center (Marland et al., 2008). This fraction peaked in 2000 at 2.7% (676 Tg CO_2 yr^{-1}) but subsequently fell as a result of events affecting aviation post 2000 but is starting to increase once more as a fraction of the total annual fossil fuel emissions of CO_2 (see Fig. 2). By comparison, annual emission rates in 2000 for global road transport, global shipping, and aviation were 4114 Tg CO_2 yr^{-1} (Eyring et al., 2005), 784 Tg CO_2 yr^{-1} (Buhaug et al., 2008), and aviation 676 Tg CO_2 yr^{-1} (this work, from IEA data), respectively. As a consequence, 12% of transportation emissions of CO_2 were from aviation and 21% of total fossil fuel emissions of CO_2 were from the total transportation sector in 2000.

Total anthropogenic emissions of CO_2 have been increasing at ever greater rates over the period 1990–2004: the rate of increase was 1.1% yr^{-1} for the period 1990–1999 and 3% yr^{-1} for the period 2000–2004 (Raupach et al., 2007) (see Fig. 2). If similar periods are considered for aviation, its CO_2 emissions increased at an average rate of 1.8% yr^{-1} for the period 1990–1999, and for the period 2000–2004 the rate of increase was slightly less at 1.6% yr^{-1} (see Fig. 2). However, this latter period was one in which aviation emission rates both declined and increased again for sectoral-specific reasons. If the period 2000–2005 is considered, aviation emissions of CO_2 increased at a rate of 2.1% yr^{-1}, mirroring the growth in total anthropogenic CO_2 emission rates over time.

The CO_2 RF from aviation or any other CO_2 source depends upon its accumulation in the atmosphere. To a first order, the atmospheric CO_2 concentration is a result of the integrated emissions over time. The integrated CO_2 emissions from aviation are given in Table 5. From 1940 to 2005, the integral is 21.3 Pg CO_2, which represents 2.1% of the emissions of fossil fuel CO_2 over that period, or 1.8% of the emissions of fossil fuel CO_2 since 1750 using the data of Marland et al. (2008). The cumulative emissions of aviation CO_2 over the period 1940 through to 2050 for the various aviation scenarios examined here are also given in Table 5. The cumulative emissions are comparable amongst the 2050 scenarios whereas the CO_2 emission rates for 2050 differ significantly, thereby explaining why the resultant CO_2 RFs for aviation in 2050 do not differ greatly.

6.2. Aviation traffic efficiency

The efficiency of aviation is improving but year-on-year emission rates are nonetheless increasing. If the trends in RPK (see Fig. 2) and ASK are examined it is clear that average load factors are increasing (Fig. 8). Also, ASK and RPK per unit fuel burn are increasing over time (Fig. 8), so that it is clear that the transport efficiency of global aviation is improving. This improvement has several factors underlying it that are difficult to disentangle and attribute. In general, traffic efficiency of the global aviation fleet is affected by load factor, system efficiency of operations (delays, routing etc.), improved technology, rate of fleet renewal and average size of aircraft.

Passenger load factors are at a historical maximum and further significant improvements are unlikely (Fig. 8) (Airbus, 2007). Considering fleet renewal brings in the complexity of the rate at which new technology enters the fleet and older aircraft are retired. The combined rate manifests itself as the average age of the global fleet, which is declining for passenger transport but generally increasing for freighter aircraft (Airbus, pers. comm.). Freighter aircraft were only 8% of the global fleet in 2006 (Airbus, 2007) but it should be noted that most freight is carried in the holds of passenger aircraft. Load factors for freight carried in passenger aircraft are not usually available because of the commercially sensitive nature of the

Table 5
Aviation emissions of CO_2 (annual and cumulative) for 2005, 2020 and 2050 from IEA data and projections made in this work as Tg CO_2 yr^{-1}. The nomenclature 'A1' and 'B2' for 2050 scenarios refers to consistency with two of the IPCC SRES GDP projections and 't1' and 't2'refers to two levels of NO_x technology as described by IPCC (1999).

Year/scenario	Fuel (Tg yr^{-1})	CO_2 emission (Tg CO_2 yr^{-1})	CO_2 cumulative emission since 1940 (Pg CO_2)
2005	232.4	733	21.3
2020	336.0	1060	34.6
2050 A1t1	816.0	2573	86.9
2050 A1t2	844.9	2665	88.2
2050 B2t1	568.8	1794	76.5
2050 B2t2	588.9	1857	77.7

data. However, by optimizing the freight-carrying-capacity, this offers further opportunities for improvement in traffic efficiency. Average aircraft size has also increased over the years both for regional (<100 seats) and larger (>100 seats) aircraft (Airbus, 2007) (Fig. 9). All these factors together tend to improve the efficiency of air traffic in terms of RPK (kg fuel)$^{-1}$. The efficiency of the air transport infrastructure is the only factor that tends to oppose overall traffic efficiency; there have been increases in delays which are symptomatic of infrastructural congestion which tends to decrease fuel and traffic efficiencies. What this complex picture shows, however, is that recent improvements have not come from better technology alone (*i.e.*, newer and more fuel-efficient aircraft), but rather from a number of factors that affect the composition of the global civil aviation fleet in terms of size, age and utilization rate.

6.3. Impacts of aviation on climate – prospects for the future

As has been shown previously by the IPCC (1999) report, a number of other assessments and this work, the climate impacts from aviation do not arise from its CO_2 emissions alone but also from other associated emissions and effects. These non-CO_2 effects in terms of RF were approximately equal to the CO_2 RF in 2005, which yields an RFI (see Section 2.4) of about 2. Including AIC effects increases the RFI to approximately 3. The RFI metric has often been misinterpreted outside of the scientific community as a multiplier to use with CO_2 emissions to give a total equivalent-CO_2 emission for future aviation scenarios. When used correctly, the RFI gives a numerical indicator of the additional climate effect associated with non-CO_2 RFs evaluated for a specific date. The magnitude of the RFI for future scenarios is largely dependent upon the growth rate of aviation emissions: if fleet emissions remained unchanged at 2005 values indefinitely, the RFI would approach a value of approximately 1.5 (excluding AIC) (Wit et al., 2005; Forster et al., 2006, 2007b). This is because the CO_2 RF increases over time from the steady accumulation of aviation CO_2 emissions in the atmosphere whilst the non-CO_2 RFs would remain constant under such a hypothetical scenario, in the absence of technological improvements.

Aviation currently contributes a small but significant radiative forcing of climate change, estimated to be between 3.5% (1.3–10%, 90% likelihood range) and 4.9% (2.0–14%, 90% likelihood range) of total anthropogenic RF, depending on whether the AIC RF is excluded or included, respectively. The aviation contribution (excluding AIC) is projected to grow by a factor of approximately 3–4 by 2050, becoming an increasing proportion of total anthropogenic RF (4–4.7%) (Table 4). As has been shown, the overall transport efficiency of aviation is improving but these factors are already built into the emission scenarios analysed here. Thus, the future total aviation RF likely will depend most strongly on the growth rate of aviation and less on the rate of technological and fleet improvement as currently envisaged on the basis of evolutionary technology development.

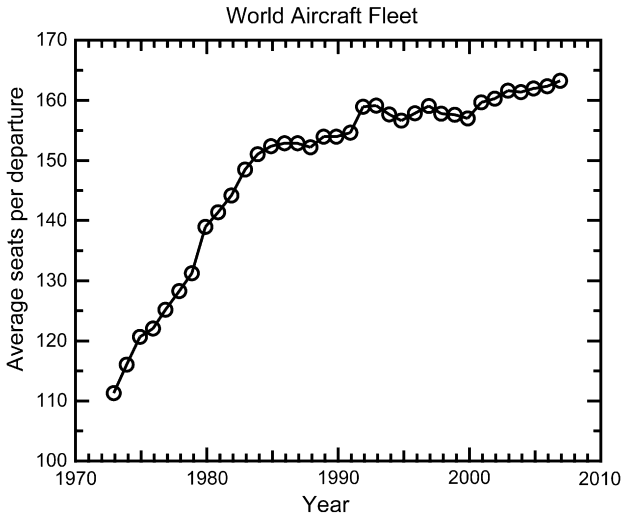

Fig. 9. Change in average aircraft size in the global fleet in terms of average number of seats per departure (source, Airbus, 2007).

Between 2005 and 2007, traffic increased by a further 12.9% in terms of RPK, so that the total growth of RPK between 2000 and 2007 was 38% (IEA fuel data were not available post 2006 at the time of writing). In the period 2007–2008, fuel prices increased dramatically and this may impact upon the future growth rate of aviation. Mitigation measures by technological means could potentially slow the rate at which aviation RF increases. Other measures include market-based and regulatory measures. Market-based measures are usually preferred by many sectors, including aviation. In this class of measures, the primary contender is emissions trading, which in the case of aviation is largely seeking to reduce CO_2 emissions under a 'cap and trade' scheme. There are prospects for a regional scheme being implemented in the next 5 years or so within the EU that includes all internal EU traffic plus all arriving and departing aircraft (see Section 5.3). The overall geographical scope of the envisaged scheme may be legally challenged by non-EU States. However, more recent developments (*e.g.*, in Australia (Anon, 2008; Garnaut, 2008)) potentially open up the possibility for regional linkage of schemes if issues of compatibility can be overcome.

7. Conclusions

The IPCC has addressed aviation through its WGI and WGIII in the Fourth Assessment Reports published in 2007 (IPCC, 2007). WGI evaluated RF for aviation cloudiness in 2005 on the basis of available 2000 estimates and WGIII evaluated the proportion that aviation RF represented of total anthropogenic forcing in 2005.

In the present study, data were presented to show significant traffic growth and increases in global aviation fuel usage and RPK between 2000 and 2005. Traffic data were available up until 2007, which showed an increase of RPK of 38% between 2000 and 2007 (average growth rate of 5.3% yr^{-1}). The increases occurred despite a number of world-changing events such as the Gulf War and SARS that threatened global aviation use. The recalculated aviation RFs for 2005 revealed a total of 55 mW m^{-2} (excluding AIC), a 14% increase over the 2000 value assumed by IPCC (2007). In addition, PDFs were derived to represent the uncertainty in each aviation component in a manner consistent with previous analyses. The PDFs were combined using a Monte Carlo analysis to derive a PDF for the total aviation RF and the fraction it represents of total anthropogenic RF. From these, the 2005 aviation total RF of 55 mW m^{-2} has a 90% likelihood range of 23–87 mW m^{-2}, excluding AIC. Including AIC yields a median value of 78 mW m^{-2} with a 90% likelihood range of 38–139 mW m^{-2}. These new results indicate that aviation represents a 3.5% share of total anthropogenic forcing in 2005 (90% likelihood range of 1.3–10%), excluding AIC, or a 4.9% share (90% likelihood range of 2–14%) including AIC. Thus, an aviation contribution larger than 14% is very unlikely (less than 5% probable) based on present knowledge.

Several 2050 scenarios were constructed for future potential aviation fuel use and emissions. Forecasts of RPK were used from ICAO/FESG to calculate emissions in 2020 and further projections of RPK to 2050 were linked to GDP scenarios from the IPCC. Aviation emissions were then derived from the RPK estimates with assumptions defining the aviation fleet traffic efficiencies. From emissions, RF values were calculated using scaling methodologies. For a forecast of traffic growth

out to 2020, the overall forcing was estimated to be 84 mW m^{-2}, which is a factor of 1.7 greater than that calculated for 2000. Two further aviation growth scenarios out to 2050 were derived mirroring the IPCC A1 and B2 scenarios with two NO_x technology variants (t1 and t2). The aviation RF for the 2050 A1t1 scenario of 194 mW m^{-2} represents an increase of a factor of 4.0 over 2000, and the value for the 2050 B2t1 scenario of 154 mW m^{-2} is an increase of a factor of 3.2 over 2000. Both scenarios assume improvements of technology that were anticipated previously by IPCC (1999). AIC RFs for all the 2020 forecast and 2050 scenarios were scaled by fuel usage from the 2005 AIC RF value but are not included in the RF totals presented here. The methods by which the 2050 RFs have been calculated are simplified, particularly for O_3, CH_4 and contrail impacts. As such, the results presented here are indicative and should be followed up with a larger-scale international multi-model effort. In the case of AIC, we highlight that no process-based model has yet been presented in the literature and there is an urgent need for such modelling.

A range of options and possibilities for reducing emissions from aviation, focussing mainly on CO_2, was considered by IPCC AR4 WGIII ('maximum feasible reductions'). For substantial emissions reductions, new and radical technologies will need to be introduced such as blended wing body aircraft and unducted-propfan engines. There are few prospects at the moment for alternative fuels such as liquid hydrogen to make substantial emissions savings and the utility of using biofuels in the aviation sector remains uncertain, principally because of the stringent requirements over fuel composition for reasons of safety. A limited range of scenarios was examined to estimate what degree of CO_2 saving could be made by 2030. The potential savings are limited because of the long-lifetime of new aircraft; for example, the fleet in 2030 will substantially comprise the best of today's technology, which has been delivering diminishing returns in terms of fuel efficiency. All 2030 scenarios resulted in increased emissions in line with the underlying growth of passenger demand ranging from 2.0 to 3.3 times 2002 CO_2 emissions. Policies and measures have been difficult to formulate for the aviation sector in relation to CO_2; fuel taxation is unpopular with many countries and emissions trading has had only limited proposed implementation. Currently, the only proposal for a legal policy framework that directly addresses targeted reduction of aviation CO_2 emissions is that of the EU which intends to incorporate aviation into its wider emissions trading scheme in a phased manner in 2012. Determination of how or if to account for non-CO_2 effects of aviation in climate policy remains of importance, not only for realising the full potential for climate change mitigation, but also for the acceptance of any policy by the stakeholder community.

Acknowledgements

This work was supported by the United Kingdom Department for Transport, the European Commission Sixth Framework Project 'QUANTIFY' (contract no 003893-GOCE, http://ip-quntify.eu) and the Higher Education Innovation Fund for England project 'Omega' (http://www.omega.mmu.ac.uk). DF/NOAA is supported by the NOAA Atmospheric Composition and Climate Program (ACCP). We would also like to thank Professor Bernd Kärcher of DLR and a reviewer for extensive and constructive comments. Dr Christine Bickerstaff of Airbus UK was extremely helpful in providing Airbus data (Fig. 9). The views presented here are those of the authors and do not necessarily represent the views of their respective organizations.

References

Airbus, 2007. Global Market Forecast 2006–2026. Airbus, France.

Anonymous, 2008. Emissions trading scheme discussion paper. Garnaut Clim. Change. Rev. March 2008.

Baughcum, S.L., Henderson, S.C., Tritz, T.G., Pickett, D.C., 1996. Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis. NASA CR4700. NASA, Langley Research Center, Hampton, VA, USA.

Baughcum, S.L., Sutkus Jr., D.J., Henderson, S.C., 1998. Year 2015 Aircraft Emission Scenario for Scheduled Air Traffic. NASA-CR-1998-207638. National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA, 44 pp.

Berghof, R., Schmitt, A., Eyers, C., Haag, K., Middel, J., Hepting, M., Grübler, A., Hancox, R., 2005. CONSAVE 2050. Final Technical Report. DLR, Köln, Germany.

Boucher, O., Haywood, J., 2001. On summing the components of radiative forcing of climate change. Clim. Dyn. 18, 297–302.

Brasseur, G.P., Cox, R.A., Hauglustaine, D., Isaksen, I., Lelieveld, J., Lister, D.H., Sausen, R., Schumann, U., Wahner, A., Wiesen, P., 1998. European assessment of the atmospheric effects of aircraft emissions. Atmos. Environ. 32, 2329–2418.

Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Mjelde, A., Pålsson, C., Wanquing, W., Winebrake, J.J., Yoshida, K., 2008. Updated Study on Greenhouse Gas Emissions from Ships: Phase I Report. International Maritime Organization (IMO), London, UK.

Caldeira, K., Hoffert, M.I., Jain, A., 2000. Simple ocean carbon cycle models. In: Wigley, T.M.L., Schimel, D.S. (Eds.), The Carbon Cycle. Cambridge University Press, UK.

Daggett, D., Hendricks, R.C., Walther, R., Corporan, E., 2008. Alternate Fuels for Use in Commercial Aircraft. NASA/TM. 2008-214833, ISABE–2007–1196. National Aeronautics and Space Administration, Glenn Research Center, Cleveland, Ohio, USA.

Derwent, R.G., Collins, W.J., Johnson, C.E., Stevenson, D.S., 2001. Transient behaviour of tropospheric ozone precursors in a global 3-D CTM and their indirect greenhouse effects. Clim. Change 49, 463–487.

EC, 2006. Impact Assessment. Commission Staff Working Document (COM 2006) 818 Final, Accompanying Document to the Proposal for the European Parliament and the Council. amending Directive 2003/87. EC, Brussels.

Eleftheratos, K., Zerefos, C.S., Zanis, P., Balis, D.S., Tselioudis, G., Gierens, K., Sausen, R., 2007. A study on natural and manmade global interannual fluctuations of cirrus cloud cover for the period 1984–2004. Atmospheric Chem. Phys. 7, 2631–2642.

Eyers, C.J., Addleton, D., Atkinson, K., Broomhead, M.J., Christou, R., Elliff, T., Falk, R., Gee, I., Lee, D.S., Marizy, C., Michot, S., Middel, J., Newton, P., Norman, P., Plohr, M., Raper, D., Stanciou, R., 2005. AERO2K Global Aviation Emissions Inventories for 2002 and 2025. QINETIQ/04/0113. Farnborough, UK).

Eyring, V., Köhler, H.W., van Aardenne, J., Lauer, A., 2005. Emissions from international shipping: 1. The last 50 Years. J. Geophys. Res. 110, D17305. doi:10.1029/2004JD005619.

Eyring, V., Stevenson, D.S., Lauer, A., Dentener, F.J., Butler, T., Collins, W.J., Ellingson, K., Gauss, M., Hauglustaine, D.A., Isaksen, I.S.A., Lawrence, M.G., Richter, A., Rodriguez, J.M., Sanderson, M., Strahan, S.E., Sudo, K., Szopa, S., van Noije, T.P.C., Wild, O., 2007. Multi-model simulations of the impact of international shipping on atmospheric chemistry and climate in 2000 and 2030. Atmos. Chem. Phys. 7, 757–780.

FESG, 1998. Report 4. Report of the Forecasting and Economic Analysis Sub-Group (FESG): Long-Range Scenarios. International Civil Aviation Organization Committee on Aviation Environmental Protection Steering Group Meeting, Canberra, Australia, January 1998, 131 pp.

Fichter, C., Marquart, S., Sausen, R., Lee, D.S., 2005. The impact of cruise altitude on contrails and related radiative forcing. Meteorol. Zeit. 14, 563–572.

Fiore, A.M., West, J.J., Horowitz, L.W., Naik, V., Schwarzkopf, M.D., 2008. Characterizing the tropospheric ozone response to methane emission controls and the benefits to climate and air quality. J. Geophys. Res. 113, D08307. doi:10.1029/2007JD009162.

Forster, P.M., Shine, K.P., Stuber, N., 2006. It is premature to include non-CO_2 effects of aviation in emission trading schemes. Atmos. Environ. 40, 1117–1121.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R., 2007a. Changes in atmospheric constituents and in radiative forcing. Fourth Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change. In: Climate Change. Cambridge University Press, UK.

Forster, P.M., Shine, K.P., Stuber, N., 2007b. Correction to 'It is premature to include non-CO2 effects of aviation in emission trading schemes' (vol 40, pg 1117, 2006). Atmos. Environ. 41 3941.

Friedl, R.R., Baughcum, S.L., Anderson, B., Hallett, J., Liou, K.N., Rasch, P., Rind, D., Sassen, K., Singh, H., William, L., Wuebbles, D., 1997. Atmospheric Effects of Subsonic Aircraft: Interim Assessment of the Advanced Subsonic Assessment Program. NASA Reference Publication 1400, Washington DC, USA.

Fuglestvedt, J.S., Berntsen, T.K., Godal, O., Sausen, R., Shine, K.P., Skodvin, T., 2003. Metrics of climate change: assessing radiative forcing and emissions indices. Climatic Change 58, 267–331.

Fuglestvedt, J., Berntsen, T., Myhre, G., Rypdal, K., Bielvedt-Skeie, R., 2008. Climate forcing from the transport sectors. Proc. Nat. Acad. Sci. 105. doi:10.1073/pnas.0702958104.

Fuglestvedt, J.S., Shine, K.P., Cook, J., Berntsen, T., Lee, D.S., Stenke, A., Skeie, R.B., Velders, G., Waitz, I.A. Assessment of transport impacts on climate and ozone: metrics. Atmos. Environ., in press.

Gardner, R.M., Adams, J.K., Cook, T., Larson, L.G., Falk, R.S., Fleuit, E., Förtsch, W., Lecht, M., Lee, D.S., Leech, M.V., Lister, D.H., Massé, B., Morris, K., Newton, P.J., Owen, A., Parker, E., Schmitt, A., ten Have, H., Vandenberghe, C., 1998. ANCAT/EC2 Aircraft Emissions Inventories for 1991/1992 and 2015. Final Report.

Produced by the ECAC/ANCAT and EC Working Group. European Civil Aviation Conference.
Garnaut, 2008. The Garnaut Climate Change Review. final report, September 2008. Cambridge University Press, UK.
Gauss, M., Isaksen, I.S.A., Lee, D.S., Søvde, O.A., 2006. Impact of aircraft NO_x emissions on the atmosphere—tradeoffs to reduce the impact Atmos. Chem. Phys. 6, 1529–1548.
Gierens, K., Sausen, R., Schumann, U., 1999. A diagnostic study of the global distribution of contrails. Part II: future air traffic scenarios. Theor. Appl. Climatol. 63, 1–9.
Greene, D.L., 1992. Energy-efficiency improvement potential of commercial aircraft. Ann. Rev. Energy Environ. 17, 537–574.
Grewe, V., Dameris, M., Hein, R., Köhler, I., Sausen, R., 1999. Impact of future subsonic NO_x emissions on the atmospheric composition. Geophys. Res. Lett. 26, 47–50.
Grewe, V., Dameris, M., Fichter, C., Lee, D.S., 2002. Impact of aircraft NO_x emissions. Part 2: effects of lowering the flight altitude. Meteorol. Zeit 11, 197–205.
Grewe, V., Stenke, A., 2008. AirClim: an efficient tool for climate evaluation of aircraft technology. Atmos. Chem. Phys. 8, 4621–4639.
Hasselmann, K., Hasselmann, S., Giering, R., Ocana, V., von Storch, H., 1997. Sensitivity study of optimal CO_2 emission paths using a Simplified Structural Integrated Assessment Model (SIAM). Climatic Change 37, 345–386.
Henderson, S.C., Wickrama, U.K., Baughcum, S.L., Begin, J.J., Franco, F., Greene, D.L., Lee, D.S., McLaren, M.L., Mortlock, A.K., Newton, P.J., Schmitt, A., Sutkus, D.J., Vedantham, A., Wuebbles, D.J., 1999. Aircraft emissions: current inventories and future scenarios. In: Penner, J.E., Lister, D.H., Griggs, D.J., Dokken, D.J., McFarland, M. (Eds.), 'Aviation and the Global Atmosphere', Intergovernmental Panel on Climate Change. Cambridge University Press, UK.
Hendricks, J., Kärcher, B., Lohmann, U., Ponater, M., 2005. Do aircraft black carbon emissions affect cirrus clouds on the global scale? Geophys. Res. Lett. 32, L12814. doi:10.1029/2005GL022740.
ICAO. Journal, issue 05, 2007.
ICAO/FESG, 2003. FESG CAEP-SG20031-IP/8 10/6/03. Steering Group Meeting Report of the FESG/CAEP6 Traffic and Fleet Forecast. Forecasting Sub-group of FESG, Orlando. SG meeting, June 2003.
IEA, 2007. Oil Information 2006, Table 9, 749 pp.. International Energy Agency, Paris.
IPCC, 1999. Aviation and the global atmosphere. In: E Penner, J., Lister, D.H., Griggs, D.J., Dokken, D.J., McFarland, M. (Eds.), Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
IPCC, 2000. Emissions Scenarios. A Special Report of WG III of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK.
IPCC, 2001. Climate change 2001: the scientific basis. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK.
IPCC, 2007. Climate change 2007. The physical science basis. In: Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M.M.B., Miller, H.L., Chen, Z. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK.
Jaeglé, L., Jacob, D.J., Brune, W.H., Tan, D., Faloona, I.C., Weinheimer, A.J., Ridley, B.A., Campos, T.L., Sachse, G.W., 1998. Sources of HO_x and production of ozone in the upper troposphere over the United States. Geophys. Res. Lett. 25, 1709–1712.
Jelinek, F., Carlier, S., Smith, J., Quesne, A., 2002. The EUR RVSM Implementation Project—Environmental Benefit Analysis. EUROCONTROL, Brussels, Belgium, 77 pp.
Johnson, C.E., Collins, W.J., Stevenson, D.S., Derwent, R.G., 1999. Relative roles of climate and emissions changes on future tropospheric oxidant concentrations. J. Geophys. Res. 104, 18631–18645.
Kahn-Ribeiro, S., Kobayashi, S., Beuthe, M., Gasca, J., Greene, D., Lee, D.S., Muromachi, Y., Newton, P.J., Plotkin, S., Wit, R.C.N., Zhou, P.J., 2007. Transportation and its infrastructure. In: 'Mitigation of Climate Change' Fourth Assessment Report Working Group III, Intergovernmental Panel on Climate Change. Cambridge University Press, UK.
Kärcher, B., Turco, R.P., Yu, F., Danilin, M.Y., Weisenstein, D.K., Miake-Lye, R.C., Busen, R., 2000. A unified model for ultrafine aircraft particle emissions. J. Geophys. Res. 105, 29379–29386.
Kärcher, B., Möhler, O., DeMott, P.J., Pechtl, S., Yu, S., 2007. Insights into the role of soot aerosols in cirrus cloud formation. Atmos. Chem. Phys. 7, 4203–4227.
Kim, B.Y., Fleming, G.G., Lee, J.J., Waitz, I.A., Clarke, J.P., Balasubramanian, S., Malwitz, A., Klima, K., Locke, M., Holsclaw, C.A., Maurice, L.Q., Gupta, M.L., 2007. System for assessing Aviation's Global Emissions (SAGE), Part 1: model description and inventory results. Trans. Res. D12, 325–346.
Köhler, M.O., Rädel, G., Dessens, O., Shine, K.P., Rogers, H.L., Wild, O., Pyle, J.A., 2008. Impact of perturbations to nitrogen dioxide emissions from global aviation. J. Geophys. Res. 113, D11305. doi:10.1029/2007JD009140.
Kuhn, P.M., 1970. Airborne observations of contrail effects on the thermal radiation budget. J. Atmos. Sci. 27, 937–942.
Lee, D.S., Owen, B., Graham, A., Fichter, C., Lim, L.L., Dimitriu, D., 2005. Allocation of International Aviation Emissions from Scheduled Air Traffic – Present Day and Historical (Report 2 of 3). Manchester Metropolitan University, Centre for Air Transport and the Environment, Manchester, UK. http://www.cate.mmu.ac.uk/project_view.asp?chg=projects&chg2=2&id=2 CATE-2005-3(C)-2See(accessed 18.02.09).
Lim, L.L., Lee, D.S., Sausen, R., Ponater, M., 2007. Quantifying the effects of aviation on radiative forcing and temperature with a climate response model. In: Sausen, R., Blum, A., Lee, D.S., Brüning, C. (Eds.), Proceedings of an International Conference on Transport, Atmosphere and Climate (TAC). Office for Official Publications of the European Communities, Luxembourg, ISBN 92-79-04583-0, pp. 202–207. See. http://www.pa.op.dlr.de/tac/proceedings.html (accessed 18.02.09).
Maier-Reimer, E., Hasselmann, K., 1987. Transport and storage of CO_2 in the ocean – an inorganic ocean-circulation carbon cycle model. Clim. Dyn. 2, 63–90.
Mannstein, H., Spichtinger, P., Gierens, K., 2005. A note on how to avoid contrail cirrus. Trans. Res. 10D, 421–426.
Marland, G., Andres, B., Boden, T., 2008. Global CO2 Emissions from Fossil-fuel Burning, Cement Manufacture and Gas Flaring 1751–2005. Carbon Dioxide Information Analysis Center. online data. http://cdiac.ornl.gov/ftp/ndp030/global.1751_2005.ems (accessed 20.09.08).
Marquart, S., Sausen, R., Ponater, M., Grewe, V., 2001. Estimate of the climate impact of cryoplanes. Aero. Sci. Technol. 5, 73–84.
Marquart, S., Ponater, M., Mager, F., Sausen, R., 2003. Future development of contrail cover, optical depth, and radiative forcing: impacts of increasing air traffic and climate change. J. Clim. 16, 2890–2904.
Meehl, G.A., Collins, W.D., Friedlingstein, P., Gaye, A.T., Grogory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.-C., 2007. Global climate projections. In: 'Climate Change', Fourth Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK.
Meerkötter, R., Schumann, U., Doelling, D.R., Minnis, P., Nakajima, T., Tsushima, Y., 1999. Radiative forcing by contrails. Ann. Geophys. 17, 1080–1094.
Minnis, P., Ayers, J.K., Palikonda, R., Phan, D., 2004. Contrails, cirrus trends, and climate. J. Clim. 17, 1671–1685.
Myhre, G., Highwood, E.J., Shine, K.P., Stordal, F., 1998. New estimates of radiative forcing due to well mixed greenhouse gases. Geophys. Res. Lett. 25, 2715–2718.
Owen, B., Lee, D.S., 2006. Allocation of International Aviation Emissions from Scheduled Air Traffic – Future Cases, 2005 to 2050. Centre for Air Transport and the Environment, Manchester Metropolitan University, UK. CATE-2006-3(C)-3. See. http://www.cate.mmu.ac.uk/project_view.asp?chg=projects&chg2=2&id=2 (accessed 18.02.09).
Ponater, M., Pechtl, S., Sausen, R., Schumann, U., Hüttig, G., 2006. Potential of the cryoplane technology to reduce aircraft climate impact: a state-of-the-art assessment. Atmos. Environ. 40, 6928–6944.
Prather, M., Sausen, R., Grossman, A.S., Haywood, J.M., Rind, D., Subbaraya, B.H., 1999. Potential climate change from aviation. In: Penner, J.E., Lister, D.H., Griggs, D.J., Dokken, D.J., McFarland, M. (Eds.), 'Aviation and the Global Atmosphere', Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G.Y., Solomon, S., 2001. Radiative forcing of climate change. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, UK Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.
Raupach, M.R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J.G., Klepper, G., Field, C.B., 2007. Global and regional drivers of accelerating CO_2 emissions. Proc. Nat. Acad. Sci. doi:10.1073/pnas.0700609104.
Reinking, R.F., 1968. Insolation reduction by contrails. Weather 23, 171–173.
Resource Analysis, 1999. Analysis of the Taxation of Aircraft Fuel. MVA Limited, Dutch National Aerospace Laboratory and International Institute of Air and Space Law. 1999: Produced for European Commission, Delft, The Netherlands.
Rogers, H.L., Lee, D.S., Raper, D.W., de, F., Forster, P.M., Wilson, C.W., Newton, P.J., 2002. The impacts of aviation on the atmosphere. The Aeronautical J. 106, 521–546.
Sausen, R., Gierens, K., Ponater, M., Schumann, U., 1998. A diagnostic study of the global distribution of contrails part I: present day climate. Theor. Appl. Climatol. 61, 127–151.
Sausen, R., Isaksen, I., Grewe, V., Hauglustaine, D., Lee, D.S., Myhre, G., Köhler, M.O., Pitari, G., Schumann, U., Stordal, F., Zerefos, C., 2005. Aviation radiative forcing in 2000: an update of IPCC (1999). Meteorol. Zeit 114, 555–561.
Sausen, R., Schumann, U., 2000. Estimates of the climate response to aircraft CO_2 and NO_x emissions scenarios. Clim. Change 44, 27–58.
Schumann, U., 1997. The impact of nitrogen oxides emissions from aircraft upon the atmosphere at flight altitudes 8–15 km—results from the AERONOX Project. Atmos. Environ. 31, 1723–1733.
Schumann, U., 2005. Formation, properties and climatic effects of contrails. C. R. Physique 6, 549–565.
SMIC, 1971. Inadvertent Climate Modification, Report of the Study of Man's Impact on Climate. MIT Press, Cambridge, Mass., US.
Spichtinger, P., Gierens, K., Leiterer, U., Dier, H., 2003. Ice supersaturation in the tropopause region over Lindenberg, Germany. Meteorol. Zeit. 12, S.143–156. doi:10.1127/0941-2948/2003/0012-0143.
Stevenson, D.S., Doherty, R.M., Sanderson, M.G., Collins, W.J., Johnson, C.E., Derwent, R.G., 2004. Radiative forcing from aircraft NO_x emissions: mechanisms and seasonal dependence. J. Geophys. Res. 109, D17307. doi:10.1029/2004JD004759.
Stevenson, D.S., Dentener, F.J., Schultz, M.G., Ellingsen, K., van Noije, T.P.C., Wild, O., Zeng, G., Amann, M., Atherton, C.S., Bell, N., Bergmann, D.J., Bey, I., Butler, T., Cofala, J., Collins, W.J., Derwent, R.G., Doherty, R.M., Drevet, J., Eskes, H.J., Fiore, A.M., Gauss, M., Hauglustaine, D.A., Horowitz, L.W., Isaksen, I.S.A., Krol, M.C., Lamarque, J.F., Lawrence, M.G., Montanaro, V., Müller, J.F., Pitari, G., Prather, M.J., Pyle, J.A., Rast, S., Rodriguez, J.M., Sanderson, M.G., Savage, N.H., Shindell, S.T., Strahan, S.E., Sudo, K., Szopa, S., 2006. Multimodel ensemble simulations of present-day and near-future tropospheric ozone. J. Geophys. Res. 111, D08301. doi:10.1029/2005JD006338.

Stordal, F., Myhre, G., Stordal, E.J.G., Rossow, W.B., Lee, D.S., Arlander, D.W., Svenby, T., 2005. Is there a trend in cirrus cloud cover due to aircraft traffic? Atmos. Chem. Phys. 5, 2155–2162.
Stubenrauch, C.J., Schumann, U., 2005. Impact of air traffic on cirrus coverage. Geophys. Res. Lett. 32, L14813. doi:10.1029/2005GL022707.
Sutkus, D.J., Baughcum, S.L., DuBois, D.P., 2001. Scheduled Civil Aircraft Emission Inventories for 1999: Database Development and Analysis. National Aeronautics and Space Administration, Glenn Research Centre. NASA CR-2001/211216.
Tompkins, A.M., Gierens, K., Rädel, G., 2007. Ice supersaturation in the ECMWF integrated forecast system. Q. J. Roy. Meteorol. Soc. 133, 53–63.
Wardle, D.A., 2003. Global sale of green air travel supported using biodiesel. Renewable Sustainable Energy Rev. 7, 1–64.
Wigley, T.M., 2004. MAGICC/SCENGEN User Manual. NCAR, Boulder, CO, USA.
Wigley, T.M.L., Smith, S.J., Prather, M.J., 2002. Radiative forcing due to reactive gas emissions. J. Clim. 15, 2690–2696.
Wild, O., Prather, M.J., Akimoto, H., 2001. Indirect long-term global radiative cooling from NO_x emissions. Geophys. Res. Lett. 28, 1719–1722.
Wit, R.C.N., Dings, J.M.W., 2002. Economic Incentives to Mitigate Greenhouse Gas Emissions from International Aviation. CE-Delft, Delft, The Netherlands.
Wit, R.C.N., Boon, B., van Velzen, A., Cames, M., Deuber, O., Lee, D.S., 2005. Giving Wings to Emission Trading; Inclusion of Aviation Under the European Emission Trading System (ETS). Design and Impacts CE-Delft, Delft, The Netherlands.
Wuebbles, D., Gupta, M., Ko, M., 2007. Evaluating the impacts of aviation on climate change. Eos Trans. AGU 88 (14), 157. doi:10.1029/2007EO140001.
Zerefos, C.S., Eleftheratos, K., Balis, D.S., Zanis, P., Tselioudis, G., Meleti, C., 2003. Evidence of impact of aviation on cirrus cloud formation. Atmos. Chem. Phys. 3, 1633–1644.