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[1]Rogers H. L., [2]Lee D. S., [3]Raper D. W., [4]Forster P. M. de F., [2]Wilson C. W. and [5]Newton P.

[1]European Ozone Research Coordinating Unit, University of Cambridge, Department of Chemistry, Cambridge, UK

[2]QinetiQ, Centre for Aerospace Technology, Cody Technology Park, Farnborough, UK

[3]Manchester Metropolitan University, ARIC, Department of Environmental and Geographical Sciences, Manchester UK

[4]The University of Reading, Department of Meteorology, Reading, UK

[5]Department of Trade and Industry, Engineering Directorate, Aviation Environmental Affairs, London, UK

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Authorization

Prepared by	Prof. David S. Lee
Title	Technology Chief – Atmospheric Science
Signature	
Date	
Location	Centre for Aerospace Technology, Cody Technology Park, Farnborough
	25-02-2002
Authorized by	Dr Roger A. Onions
Title	Technical Manager, Propulsion, Centre for Aerospace Technology
Signature	
Date	06-03-2002

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Abstract

This paper provides the current status of knowledge regarding the impact of aviation on the atmosphere. The growth of the aviation industry is likely to continue in the future and at present there are significant concerns that this will adversely affect climate, and local air quality in the vicinity of airports. Indeed, it is possible that air quality may become a constraint to increased capacity of some large hub airports. Currently the radiative forcing impacts from aircraft emissions, other than CO_2, are not accounted for in the International Civil Aviation Organization emission trading scheme proposals. Taking only this approach, emissions trading could, in theory, increase the radiative forcing, rather than decrease it. The study of improved 'environmentally friendly' flight is still in its infancy; however, any proposed and actual new developments, in terms of technology and operational practice, should include an environmental assessment.

Executive summary

Aviation's impacts on the atmosphere include effects on local air quality and climate. In this paper we review the state of knowledge of these impacts.

Aviation has undergone remarkable growth, at a rate exceeding increases in global gross domestic product. This growth, over long time periods, is expected to continue averaging approximately 5% per year, despite the recent economic downturn. Commensurate with this growth has been a pressure upon the environmental performance of aviation: significant progress has been made on increasing overall fuel efficiency, thus reducing carbon dioxide emissions, through both technology and operational management. Levels of other pollutants such as nitrogen oxides, smoke, hydrocarbons and carbon monoxide have also been reduced through technological advances. Historically, environmental pressures on aviation came from local air quality concerns—principally health driven—and also concerns over damage to the stratospheric ozone layer from propositions in the early 1970s for the development of a large fleet of supersonic aircraft. Over the last 20 years or so, these pressures have changed to concerns over the current (and future) subsonic fleet's potential effects on climate change. These concerns led to the Intergovernmental Panel on Climate Change's (IPCC) major assessment report '*Aviation and the Global Atmosphere*' (IPCC,1999). Since then, air quality concerns have increased because of growth in the aviation sector that is no longer matched by the earlier rates of improvements in emissions at ground level: we review the state of knowledge and conclude that current air quality models have limited capability and development of more appropriate models is essential.

Substantial progress has been made since the IPCC report, addressing some of the major questions that were posed. Recent climate modelling studies have shown that the formation of tropospheric ozone, a powerful greenhouse gas, from aviation emissions of nitrogen oxides remains an issue. There are significant questions over this effect that require more study. The formation of contrails and enhancement of cirrus cloud coverage were also highlighted by the IPCC as having a potentially large radiative forcing. EU Research programmes are currently underway to address the basic physics of these processes. Recent modelling of contrail radiative forcing has shown divergent results from those given by the IPCC. This indicates the strong level of uncertainty remaining over contrail radiative forcing and more research should be devoted to this area.

Questions are being posed on the extent to which aircraft traffic management has the potential to ameliorate some of the effects of aircraft emissions: initial studies to address this issue are in progress within EU research programmes. Recent technological developments, such as the 'Sonic Cruiser' re-open issues upon stratospheric impacts on climate forcing. International aviation emissions of carbon dioxide (CO_2) are not covered by the Kyoto Protocol. However, it remains clear that aviation's impact on climate is quantitatively more than that from its CO_2 emissions alone. Currently favoured policy developments of CO_2 emissions trading do not address these other effects, as only CO_2 is covered under the Kyoto Protocol. Without addressing this deficiency, emissions trading has the potential to exacerbate the problem rather than ameliorating it.

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1 INTRODUCTION

1.1 The effects of civil aviation emissions on the atmosphere have been under discussion in recent years and there is a growing body of evidence that future growth in air traffic might result in significant impacts on local air quality and climate. Local air quality concerns usually arise from potential impacts on human health, from high concentrations of gaseous or particulate species over a relatively small area (tens of square kilometres, depending on the pollutant concerned). Global concerns relate to potential impacts of emissions on climate change. Other than carbon dioxide (CO_2), the emission regime of the so-called 'Landing/Take Off cycle' (LTO) relates to air quality concerns whilst emissions during climb, cruise and descent relate to climate impacts.

1.2 Aviation has undergone spectacular growth, outstripping GDP as globalization of industry and commerce has increased. Aviation is a fundamental part of business and commerce, and is a wealth-creator. In some senses, the 'spotlight' has been turned on aviation because of its own success. Considering aviation growth, there are many forecasts available for the future growth of civil aviation traffic. Aerospace companies, aircraft manufacturers and airlines provide forecasts for business projections. The UK Department of Trade and Industry provides its own market forecasts, which are used to inform UK government policy. Most aviation growth forecasts rely upon assessments of global economic trends, as global GDP growth and aviation traffic growth are closely linked. Passenger traffic is expected to grow – averaging around 5.3% annually over the next 20 years (see Figure 1-1). Capacity growth (i.e. seats offered) is expected to expand at a slower rate if passenger load factors maintain their improving trend over the long term. The increased global capacity will be provided by around 14,000 new aircraft between 1999 and 2018. About half of this demand for new aircraft is derived from the replacement of existing aircraft retired from the fleet, with the other half generated by anticipated traffic growth. Over the next five years about 1,500 retirements are expected as a result of increasing environmental constraints. The environmental performance of civil aviation maintains a growing profile in social awareness and imposes pressures on the aviation industry to which it will need to respond over the long term.

1.3 The industry is, of course, susceptible to external economic and social factors. Reducing economic growth in 2001 has begun to lead to reduced traffic growth and airline profits. Compounding this the tragic events of September 11, 2001, and the current conflict in Afghanistan have precipitated a further more dramatic downturn in traffic. Operational fleets have been reduced by the early retirement or temporary storage of many older, less economic aircraft and some orders for new aircraft have been put on hold. The Gulf conflict in the early 1990s had a somewhat simi-

lar although less dramatic effect, but afterwards, growth picked up quickly and returned to the long-term trend within a few years. Once again, the aviation industry is expected to revive from this most recent decline, but it remains too early to predict the timeframe by which this might be achieved. Accordingly, the original forecasts of growth have been retained for this paper.

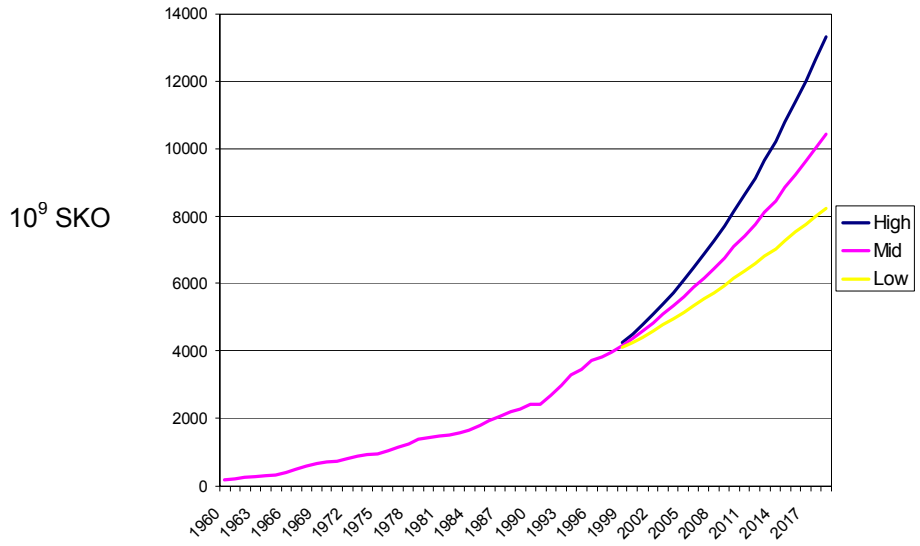


Figure 1-1 Aviation growth in terms of global SKO (10^9 seat kilometres offered) between 1960 and 2020 (source: DTI data)

1.4 There are differing views as to the possible composition of a future aircraft fleet. These views are driven as much by manufacturer ambition and long-term plans, as by the aviation industry's possible response to future demand, but they tend to be polarized into the 'fragmentation' and the 'consolidation' market views. Both models bring environmental implications at the global and airport levels.

1.5 The fragmentation view suggests that passenger preference for direct flights between individual city pairs, avoiding the necessity to route through major hubs, will imply a fleet comprising a large number of relatively small aircraft. This implies the need for possibly more airports into which these aircraft can operate. Whilst the fragmentation model implies lower noise levels and possibly lower emissions levels from individual aircraft, their greater number could counteract this effect. An increase in airport numbers would introduce noise and emissions into areas that had hitherto avoided this particular problem.

1.6 The consolidation view suggests that major hubs will be an enduring feature of the aviation scene and will be supplied by the larger aircraft of the future. The consolidation model suggests more emissions being concentrated around fewer sources, and it is feasible that aircraft emissions affecting air quality within the airport boundary may increase at a rate greater than traffic increase as aircraft become larger. This may be at least partially addressed by continuing technological developments; nonetheless, the environmental implications of these trends need to be better understood.

1.7 It is difficult to assess which view will be the more successful over the long term. However, it is clear that the economies of scale in aircraft operation are achieved by the use of larger aircraft, and larger aircraft allow lower fares; not least because of their fuel consumption characteristics and productivity. Lower fares imply continued - and probably enhanced - traffic growth and a concomitant effect on environmental impact.

1.8 An effect of the remarkable growth in air traffic has been to focus attention upon the potential environmental effects. Early turbojets emitted highly visible dark plumes on take-off, principally from soot particles, and were associated with high noise levels. Noise from aircraft is a separate issue and not dealt with here, although it is noted that stringent noise limits have vastly improved the noise levels of today's modern turbofan engines.

1.9 The emissions during the landing and take-off cycle (LTO) gave rise to concern over local air quality, prompting the US Environmental protection Agency (USEPA) to legislate against aircraft emissions. This early legislation, local to the US, later gave rise to the engine emission certification requirements of the International Civil Aviation Organization (ICAO, 1981[(1)]; most recent update ICAO, 1995[(2)]) on unburned hydrocarbons (HCs), nitrogen oxides (NO_x, where NO_x=NO+NO_2), and carbon monoxide (CO). It is worth reinforcing what these regulations are: they are design and manufacturing standards, not an in-service compliance regime. There is evidence, albeit limited, that the emissions performance of aircraft engines deteriorates between major overhauls. Overhauls are generally conducted on a time schedule basis, or when the fuel performance characteristics or exhaust gas temperatures fall outside specification margins.

1.10 Whilst local air quality was the driver for aviation emissions regulations, the initial focus on global atmospheric effects originated in the 1970s from concern that NO_x emissions in the upper atmosphere from a proposed fleet of supersonic aircraft would significantly deplete stratospheric ozone (O_3) (Johnston, 1971[(3)]; Crutzen, 1972)[(4)], resulting in increased exposure of harmful ultra violet (UV) radiation at the earth's surface. In the event, only a limited fleet was developed by the

United Kingdom and France in the form of Concorde and the large fleets envisaged were never built.

1.11 Interest in the potential effects of subsonic aircraft emissions ensued in the late 1980s and early 1990s (Schumann, 1990)[5]. This interest arose because of the growing realization that the upper troposphere and lower stratosphere, where subsonic aircraft cruise, is a rather sensitive region of the atmosphere in terms of both atmospheric chemistry and climate sensitivity. Initially, attention was focussed upon the potential effects of aircraft NO_x emissions on tropospheric O_3 production. Whereas O_3 in the mid to upper stratosphere (~15–20 km) provides a protective 'shield' against harmful UV radiation, O_3 in the upper troposphere and lower stratosphere acts as a powerful 'greenhouse gas', warming the surface. More recently, other effects such as those of contrails (condensation trails) have been studied intensively. Contrails are line-shaped ice clouds caused by the emission of water vapour and particles from the aircraft exhaust. Depending (principally) on the particular conditions of temperature and humidity, contrails may be very short-lived or persistent, sometimes spreading by wind-shear, sedimentation and diffusion into cirrus-like clouds that are ultimately unrecognisable as having been caused by aircraft. Other effects on climate from associated particle emissions and the enhancement of cirrus clouds have also been investigated.

1.12 Research into the effects of aviation on climate and O_3 depletion was synthesized in a Special Report of the Intergovernmental Panel on Climate Change – *Aviation and the Global Atmosphere* (IPCC, 1999)[6]. This was a landmark in that it was the first sectoral examination by the IPCC and estimates of radiative forcing of climate from various aircraft emissions and their effects were made. However, the IPCC was not the first assessment: other assessments and syntheses had previously been made, e.g. Schumann (1994)[7], Wahner *et al*. (1995)[8], Friedl *et al*. (1997)[9], Brasseur *et al*. (1998)[10].

1.13 This introduction would be incomplete without some overall policy backdrop. In terms of local air quality, it is often the case that aircraft emissions are a smaller fraction of the total (transportation) emissions in and around an airport. However, with increasingly stringent air quality limits and continued growth of air traffic, this situation may change in the future, particularly for large hub airports close to urban centres. In terms of climate, only domestic emissions of CO_2 are covered under the Kyoto Protocol (i.e. departure and arrival locations situated within the same country). International emissions of CO_2 from aviation are not currently covered, although ICAO's Committee on Aviation Environmental Protection (CAEP) are currently considering how these emissions may be incorporated into the Protocol.

1.14 In this paper, we aim to provide the readership with an overview of the issues; a review of the impacts of aircraft on local air quality and climate, more recent results relating to climate impacts that post-date the IPCC report; and to discuss what measures may be possible in mitigating against climate impacts. Where necessary, background material is provided. In structuring the paper, Section 2 deals with aircraft engines, their generation of pollutants and estimations of emissions. Section 3 discusses the impacts on local air quality. Section 4, by necessity the longest, provides tutorial material on the atmosphere to establish the context, and discusses the chemical and physical influences that aircraft emissions exert on the global atmosphere. The effects of aircraft emissions on global climate and the difficulties in modelling this are discussed in Section 5. In Section 6 we discuss future developments and possible mitigation approaches, and report some preliminary findings on such options. Finally, we draw overall conclusions in Section 7. In describing some of the more technical details, we have used 'boxes' to provide detailed information, should the reader be interested in a particular aspect.

2 AIRCRAFT EMISSIONS

2.1 Aircraft engine emissions

2.1.1 For reasons of economy of operation, range and market demand, there has been a constant drive towards more fuel-efficient aircraft designs. Since the introduction of civil jet aircraft approximately 40 years ago, fuel consumption per passenger-km has been reduced by approximately 70%. Most gains have been achieved through engine improvements that have exceeded the gains from airframe advancements by a ratio of 3/2. Further improvements in efficiency are forecast to continue into the future at the same rate.

2.1.2 Early research on aircraft emissions focused upon the improvements in combustor technology needed to meet the emerging LTO regulations aimed at controlling the products of inefficient combustion at low power, and NO_x and smoke at high power. Today, the focus has widened beyond the boundaries of the airport to include emissions at higher altitude. Improvements to all aircraft components are required to meet these emerging concerns. These include: the airframe; engine; operating cycle; engine components (including the inlet and compression system); the hot section consisting of combustor, turbine and exit nozzle; airframe-engine integration; and aircraft support systems.

2.1.3 Gas turbine exhausts contain concentrations of CO_2, water vapour (H_2O), NO_x, sulphur compounds (SO_x) – originating from sulphur in the fuel – and trace amounts of numerous chemical species. All of these emissions can be reduced by reducing the amount of fuel burnt, although in some cases fuel reduction through greater engine efficiency can exacerbate the combustion conditions that produce NOx. However, combustion efficiency is already > 99.95% at high power conditions such as cruise and take-off. Therefore, fuel efficiency can only be improved by improving the cycle efficiency.

2.1.4 In general, emissions of NOx, CO, HCs and particles are relevant to local air quality issues and CO_2, H_2O, NO_x, SO_x and particles are of most concern in terms of climate perturbation. The production and control of these emissions is described below.

2.1.5 Oxides of nitrogen (NOx)

2.1.5.1 Emissions of NO_x arise from the oxidation of atmospheric nitrogen in the high temperature conditions that exist in the engine's combustor, although a small amount comes from the nitrogen con-

tent of the fuel. Its production is a complex function of combustion temperature, pressure and combustor design. These emissions primarily comprise NO but are quickly converted to NO_2 in the atmosphere. The elimination of NO_x in the combustion process is virtually impossible and the control of its production to meet regulatory limits requires careful combustor design. Nitrogen oxides at the engine exit plane consist primarily of NO. The percentage of NO_2 to NO is estimated to be 1–10%, with an uncertainty of several percent. Much work, internationally, is in progress to reduce NO_x levels, with major programmes in the USA and Europe. These programmes focus upon goals well beyond in-service emission reduction capabilities, striving for NO_x reductions in the range of 60 to 70% of today's CAEP 2 regulatory NO_x standard based upon existing LTO certification requirements. The approaches being explored range from combustor sub-component performance improvements to the evolution of new and complex multi-staged combustors.

2.1.5.2 The interrelationships between NO_x–CO_2 are complex. The extent of tradeoffs between these two emissions depends upon the severity of operating conditions and the combustor emission technology. National programmes exist in Europe and USA to reduce both NO_X and CO_2 simultaneously.

2.1.6 Soot

2.1.6.1 The ICAO database 'Smoke Numbers' (ICAO, 1995)[2] define large soot particles that affect plume visibility. A fleet average emission index for soot of 0.04 g/kg fuel burned has been estimated with a large uncertainty, at best a factor of 2 (Döpelheuer *et al*., 2001)[11]. These large soot particles are thought to have only a minor direct impact upon climate (see). Of greater concern are aerosols originating in the combustor as well as those produced by the sulphur in the fuel. Measurements of aerosol emissions from aircraft, engines and combustors have been made for particles in the 3 nm to 4 μm aerodynamic diameter size range. The soot aerosol size distribution at the engine exit has been found to be log.-normal in shape with number concentrations peaking in the 40–60 nm range. Emission indices fall within the range of 10^{12} soot aerosol particles/kg fuel for current advanced combustors and to 10^{15} for older engines (Petzold *et al*., 1999)[12].

2.1.7 Trace species

2.1.7.1 At present, there is a high degree of uncertainty about the concentrations of minor trace constituents in the exhaust gases. Most of the S in the fuel (see below) is expected to be emitted as sulphur dioxide (SO_2) (Miake-Lye *et al*., 1993)[13]. However, it is thought that some oxidation through to S^{VI} (e.g. SO_3, H_2SO_4) is possible within the engine itself (Lukachko *et al*., 1998)[14].

The fraction of total gaseous S in the engine exit plane is estimated to be up to 5% S^{VI}: however, this estimate is highly uncertain. However, the emission of S species is thought to be important for volatile particle formation from sulphuric acid (H_2SO_4): gas-phase H_2SO_4 has been detected in the wake of aircraft by Curtuis *et al*. (1998)[15]. Hydroxyl radicals (OH) are produced as a part of the combustion process and may control the oxidation of NO_x and S species to their oxidized forms. Very few measurements of OH have been made, despite its importance (e.g. Hanisco *et al*., 1997)[16]. Tremmel *et al*. (1998)[17] used measurements of other odd N species to infer OH concentrations of 1 ppmv or less. However, recent static measurements using Laser Induced Fluorescence (LIF) indicate concentrations of 100 ppbv or less (Bockle *et al*., 1999)[18]. Clearly, given the importance of OH, more measurements are needed to provide upper limits for oxidation of various species within the plume.

2.1.7.2 Emissions of nitrous (HONO) and nitric (HNO_3) acids are estimated to be less than a few percent (Arnold *et al*., 1992)[19] but emission indices are rather uncertain. More measurements are needed to better quantify this speciation.

2.1.7.3 The high temperatures involved in combustion of kerosene within aircraft gas turbines produces gaseous ions by chemiionisation of free radicals, often termed 'chemi-ions' (CIs). First measurements of negative ions ($HSO_4^-H_2SO_4$, $HSO_4^-HNO_3$) were made behind an aircraft engine at ground level by Frenzel and Arnold (1994)[20]. Subsequently, other measurements have shown the presence of negative CIs in the plume of an aircraft exhaust (Arnold *et al*., 1999)[21], and positive CIs (Wohlfrom *et al*., 2000)[22]. It is thought that CIs may promote formation and growth of charged droplets (Yu and Turco, 1997)[23].

2.1.8 Fuels

2.1.8.1 Kerosene-based fuels such as those presently used in aircraft appear to be the only viable option out to the year 2050. The fuel sulphur content of aviation kerosene averages 400 to 600 ppm, although today's specifications allows for up to 3000 ppm. Removing the sulphur associated compounds from kerosene would lead to increased production costs and a small increase in CO_2 production, because of the additional energy required to make the hydrogen used to desulphurize the fuel. The process to reduce the sulphur content also degrades the quality of the fuel's natural lubricity and this can cause problems with engine fuel pumping and distribution systems. Bio-kerosene, can have zero sulphur and aromatics which may help reduce emissions, but work is required to ensure the operation and integrity of the fuel system will not be compromised by its use.

2.1.8.2 Long-term options include cryogenic fuels such as liquid methane and hydrogen. However, the use of cryogenic fuels would require revolutionary changes in aircraft design and implementation of a vast new infrastructure for supplying these fuels. Additionally, hydrogen is currently manufactured in large quantities from fossil fuels. The manufacturing process produces more CO_2 than if the fossil fuel were used directly.

2.2 Aircraft emissions – characterization and global emissions

2.2.1 Recent estimations of global aviation emissions have been conveniently summarized by Henderson *et al*. (1999)[24]. The most recent emissions estimations are for the early 1990s and three data sets are in common use: the ANCAT/EC2 dataset (Gardner *et al*., 1998)[25]; the DLR-2 data set (Schmitt and Brunner, 1997)[26]; and the NASA data set (Baughcum *et al*., 1996)[27]. Here, we focus upon the ANCAT/EC2 data set as an example (note however that the other data sets are not so very different).

2.2.2 That such data sets are out of date is self-evident; however, there is currently a European Union-funded research project underway, AERO2K, which will compile global emissions for the 2001 timeframe[1]. This project is due to report in 2003.

2.2.3 For future global emissions estimations, there are emission forecasts available for 2015 (Gardner *et al*., 1998[25]; Baughcum *et al*., 1998[28]) and scenarios for 2050 (FESG, 1998[29]; Newton and Falk, 1997[30]).

2.2.4 All the aforementioned emission data sets provide 3D gridded data and by necessity have simplifying assumptions. The essential components of an inventory include: an aircraft movements database; a representation of the global fleet in terms of aircraft and engines; a fuel-flow model; calculation of emissions at altitude from fuel flow; and landing and take-off emissions data.

2.2.5 Estimations of global fuel and NO_x for 1991/92, 2015 and 2050 are given in Table 1. The estimated global emission of NO_x (as NO_2) from civil and military aviation for the base-year of 1991/1992 is 1.81 Tg N yr^{-1} and the fuel burnt 131 Tg yr^{-1}. Military emissions, although more uncertain than the civil estimates, are approximately 11% of the total. For climate effects other than CO_2, military aviation is less important as most emissions are at much lower altitudes than those from civil aircraft. The spatial and vertical structure of emissions is shown in Figures 2-1 and 2-2,

[1] http://www.cordis.lu/fp5/projects.htm

respectively. It can be seen that much of the emissions occur in the Northern Hemisphere and at altitudes of 10 to 12 km.

Table 2-1 Fuel, CO_2, NO_x and $EINO_x$ for 1991/92, 2015 and 2050 gridded data sets

Dataset	Fuel Tg yr^{-1}	CO_2 Tg C yr^{-1}	NO_x (as NO_2) Tg yr^{-1}	$EINO_x$	Reference
ANCAT/EC2 – 1991/92	131.3	113	1.81	13.8	Gardner *et al*., 1998[25]
ANCAT/EC2 – 2015	286.9	247	3.53	12.3	Gardner *et al*., 1998[25]
DTI – 2050	633	545	4.43	7	Newton and Falk, 1997[30]
Fa1 – 2050	471.0	405	7.2	15.2	FESG, 1998[29]
Fa2 – 2050	487.6	419	5.5	11.4	FESG, 1998[29]
Fc1 – 2050	268.2	231	4.0	15.0	FESG, 1998[29]
Fc2 – 2050	277.2	238	3.1	11.3	FESG, 1998[29]
Fe1 – 2050	744.3	640	11.4	15.3	FESG, 1998[29]
Fe2 – 2050	772.1	664	8.8	11.4	FESG, 1998[29]

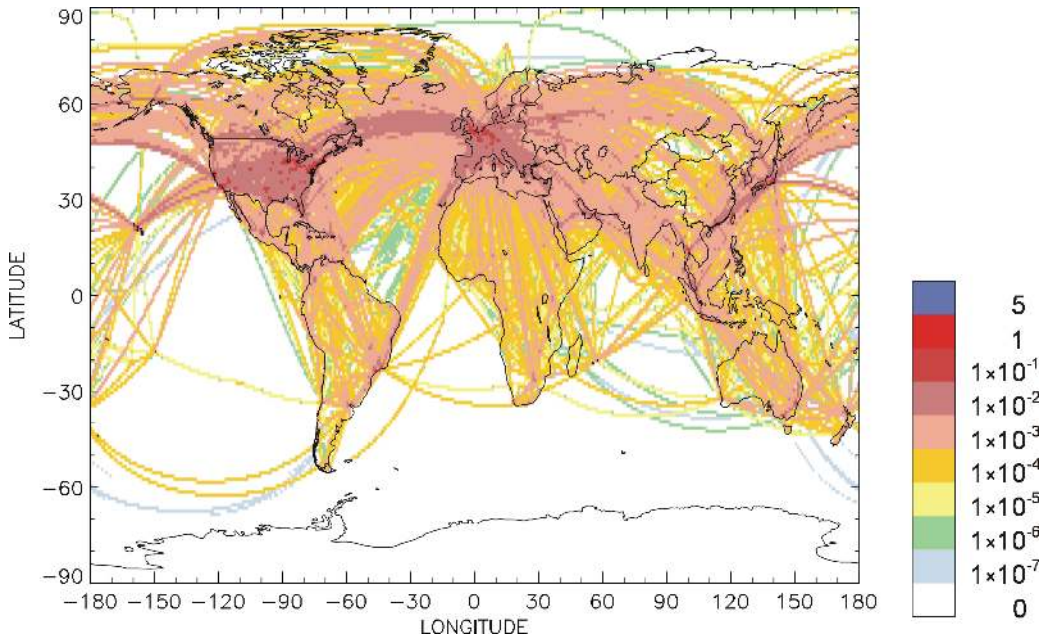


Figure 2-1 Spatial distribution of ANCAT/EC2 1991/92 emissions of NO_x from civil aviation, vertically integrated between ground and 16 km (kg NO_2 m^{-2} yr^{-1}). Source: Gardner et al. (1999)[25] and Lee et al. (2002a)[32]

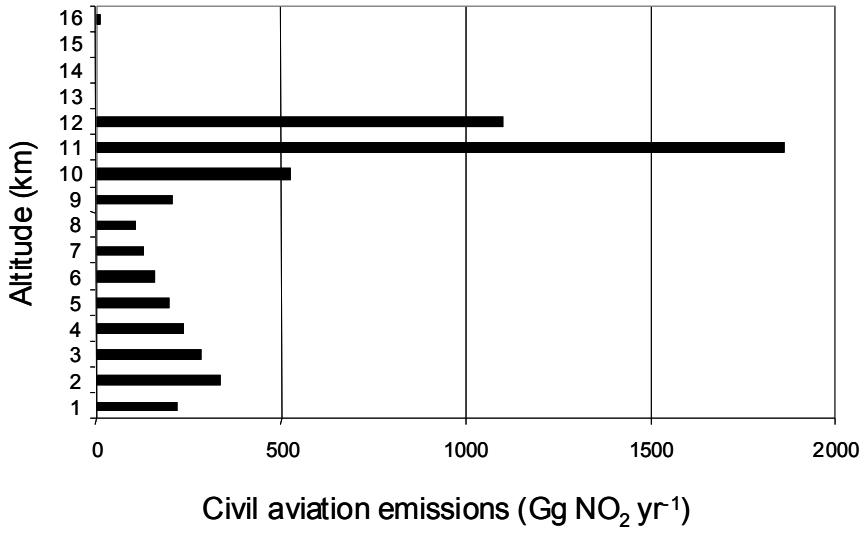


Figure 2-2 Vertical Distribution of emissions of civil aviation NO_x, 1991/92. Source: Gardner et al. (1998)[25] and Lee et al. (2002a)[32]

2.2.6 By 2015, it is forecast that emissions of NO_x (as NO_2) from civil aviation will have grown by a factor of nearly 2, to 3.53 Tg N yr^{-1} with a fuel burn of 287 Tg yr^{-1}. It is important to discriminate between forecasts and scenarios. Here, we adopt a definition of a forecast being a situation that is the result of extrapolation of current and foreseen technologies and aviation growth. For scenarios, the assumptions are greater and the approach, whilst similar in some respects, tends to be driven 'top-down'.

2.2.7 For 2050, the most commonly used gridded data sets are those generated by the Forecasting and Economic Sub Group of the ICAO (FESG, 1998)[29]. These scenarios were based upon a relationship between revenue passenger kilometres and GDP. The GDP scenarios were the IPCC 'IS92a, c and e' scenarios (Leggett *et al.*, 1992)[2] [34]. In addition, two technology scenarios for fuel and NO_x were assumed, one ambitious, one less so, giving six scenarios in total. The nomenclature adopted was, by example: Fa1—FESG IS92a Technology Scenario 1. Fuel usages

[2] Note that the IPCC IS92 scenarios have subsequently been replaced by the 'SRES' scenarios, see IPCC (2000)[33]

ranged from 268 to 772 Tg yr^{-1} and NO_x emissions by 3.1 to 11.4 Tg NO_2 yr^{-1}; these estimates equate to factors of approximately 2 to 6 on fuel and NO_x emissions over early 1990s data.

2.2.8 This potential dramatic increase is illustrated in Figure 2-3. By 2050, it is clear that assumptions in GDP growth are critical to the overall emission, the technology assumptions having a second-order effect. In contrast to this overall pattern, the DTI 2050 scenario assumes a fuel usage (from traffic growth) between the Fa and Fe scenarios (mid and upper growth scenarios, respectively) but an aggressive NO_x reduction, resulting in a global NO_x emission closer to the Fc scenario (lowest growth of the FESG scenarios). For the DTI 2050 scenario, the global fuel consumption was estimated to be 633 Tg, with 4.43 Tg of NO_x (as NO_2) produced as a consequence of a fleet $EINO_x$ of 7.

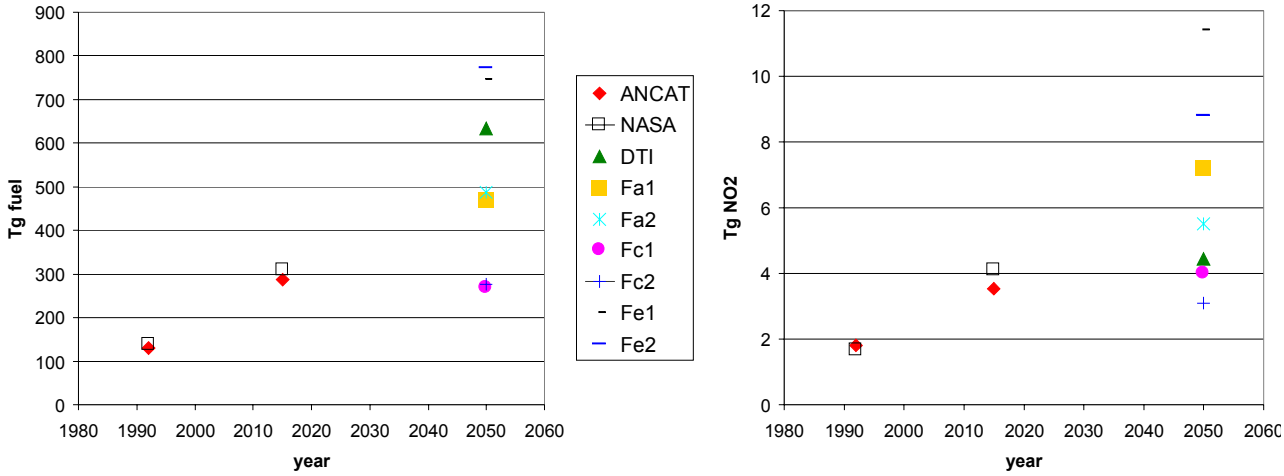


Figure 2-3 Development over time of fuel usage and NO_x emissions from aviation. Data source: IPCC (1999)[35]

2.3 Aircraft emissions in relation to other sources

2.3.1 The emissions from aircraft that can be easily compared to those from other sources are NO_x, CO_2, CO and HCs. Global particle sources are not well understood but there are indications that aircraft may be a significant source in the upper troposphere and lower stratosphere (UT/LS) (Anderson *et al.*, 1999)[36] and may influence cirrus-cloud coverage (see Section 4.4).

2.3.2 In terms of NO_x emissions, global emission budgets have been summarized by Lee *et al.* (1997)[37] and Holland *et al.* (1999)[38]. These two estimations were applicable for the late

1980s/early 1990s. These estimates were updated for 2000 by Prather and Ehalt (2001)[39] for the recent Third Assessment Report of the IPCC. Aircraft, according to the Prather and Ehalt (2001)[39] assessment, represent only 1.3% of global NO_x sources to the global troposphere. However, this low fraction should not be misunderstood as having a negligible effect on the global tropospheric O_3 budget, as sources of NO_x at altitude (including lightning NO_x), exert a more powerful effect, proportionately, on O_3 production and O_3 radiative forcing than surface sources of NO_x (see Section 4.3).

2.3.3 Prentice (2001)[40] recently analysed the global CO_2 budget and estimate fossil fuel emissions of CO_2 as being of the order 6.3 Pg C yr^{-1} for the 1990s. Based upon the ANCAT/EC2 estimation of global aviation fuel usage, this results in a CO_2 emission of 113 Tg C yr^{-1}, approximately 2% of global emissions. For the mid-range Fa1 2050 scenario, this would rise to ~3%. However, once again, this figure taken in isolation is misleading: under the Fa1 2050 scenario, aircraft would contribute 5% of the total anthropogenic radiative forcing, of which aircraft CO_2 emissions represent 38% of the aircraft total radiative forcing (IPCC, 1999).

2.3.4 The aircraft contribution to atmospheric CO and HC emissions is insignificant: 0.2 Tg yr^{-1} of CO (Hendersen *et al*., 1999)[24] in 641 Tg from fossil and domestic fuel (Bergamaschi *et al*., 2000); and 0.3 Tg yr^{-1} of HCs in 161 Tg from fossil fuel (Prather and Ehalt, 2001)[39].

3 EFFECTS ON LOCAL AIR QUALITY

3.1 Background issues

3.1.1 As discussed in Section 1, the air transport industry is a major economic generator (OEF, 1999[42]; Thomas and Raper, 2000[43]) and airports bring a wide range of social and economic benefits to the communities they serve, ranging from job creation to access to the global market. Evidently, the forecasted growth of the industry (see Section 1) will only be met by a significant increase in airport capacity. Consequently, many airports in Europe and North America are developing new infrastructure including runways and terminals in order to meet this expected increase in demand (e.g. in the UK, Heathrow Terminal 5 and Manchester 2nd Runway).

3.1.2 Concomitant to this growth, concerns over consequential degradation in air quality are increasing (e.g. Tunstall-Pedoe *et al.*, 1996)[44]. To address wider local air quality concerns, legislators within Europe and the UK have developed local air quality management as a tool to meet increasingly stringent air quality standards. The EU has promulgated a Framework Directive on Ambient Air Quality Assessment and Management (96/2/EC), commonly referred to as the Air Quality Framework Directive (Table 3.1). The UK has developed a National Air Quality Strategy, which builds upon the Framework Directive, requiring that all Local Authorities undertake an air quality assessment. Similar initiatives exist in other European countries.

3.1.3 Airports are major intermodal transport hubs and as such, they are the focus of surface transport networks, including road and rail and are generally located close to, or within, the urban fringe. In terms of local air quality, this produces a complex problem of determining the effects or impacts of aviation generated emissions on an environment that is impacted by a wide range of other emissions both in source and strength. Figure 3-1 provides a good example of the strengths and spatial coverage of emission sources around Manchester Airport. A wide range of studies has been undertaken to assess the air quality impacts of airports, particularly associated with future developments and a recent example in the UK is Stansted Airport (BAA, 2001)[45].

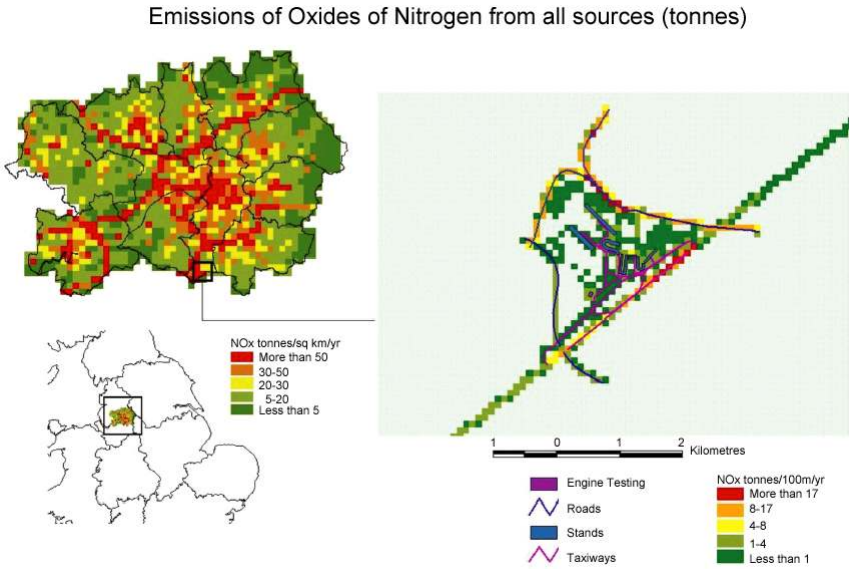


Figure 3-1 Annual emissions of NO_x at Manchester Airport and in the Greater Manchester region

Table 3-1 European Union Framework Directive and UK National Air Quality Strategy air quality limits

Pollutant	EU Framework Directive		UK National Air Quality Strategy	
	Limit value	Time-frame	Limit value	Time-frame
Benzene	–	–	16.25 µg/m^3 (5 ppb)	running annual mean
1,3 Butadiene	–	–	2.25 µg/m^3 (1 ppb)	running annual mean
Carbon monoxide	–	–	11.6 mg/m^3 (10 ppm)	running 8 hour mean
Lead	0.5 µg/m^3	annual mean	0.5 µg/m^3*	annual mean
Nitrogen dioxide	200 µg/m^3 (105 ppb)	1 hour mean not to be exceeded more than 18 times per year	200 µg/m^3 (105 ppb)	1 hour mean not to be exceeded more than 18 times per year
	40 µg/m^3 (21ppb)	annual mean		
	30 µg/m^3	annual mean for the protection of vegetation	40 µg/m^3 (21ppb)	annual mean
Particles (PM_{10})	Stage 1			
	50 µg/m^3	24 hour mean not be exceeded more than 35 times a year	50 µg/m3	24 hour mean not be exceeded more than 35 times a year
	Stage 2		40 µg/m^3	annual mean
	40 µg/m^3	annual mean		
	50 µg/m^3	24 hour mean not be exceeded more than 35 times a year		
	20 µg/m^3	annual mean		
Sulphur dioxide	350 µg/m^3 (132 ppb)	1 hour mean not to be exceeded more than 24 times a year	350 µg/m^3 (132 ppb)	1 hour mean not to be exceeded more than 24 times a year
	125 µg/m^3 (47 ppb)	24 hour mean not to be exceeded more than 3 times a year	125 µg/m^3 (47 ppb)	24 hour mean not to be exceeded more than 3 times a year
			266 µg/m^3 (100 ppb)	15 minute mean not to be exceeded more than 35 times a year

3.2 Key pollutants

3.2.1 Numerous pollutants are emitted from aviation fuel combustion and other airport activities. The most important of these are NO_x, HCs (also referred to by the broader term volatile organic compounds–VOCs–which includes carbon in combination with elements other than hydrogen), CO and particulate matter.

3.2.2 Oxides of nitrogen

3.2.2.1 The most important oxidized N species in terms of air quality terms is NO_x. Nitrogen oxides are emitted from aircraft and fuel combustion processes including vehicles and fixed plant. Within airport environs, the major sources of NO_x are motor vehicles, stationary plant and aircraft engines.

3.2.3 Carbon monoxide

3.2.3.1 The major sources of CO within airport environs are petrol and diesel engine motor vehicles, stationary plant and aircraft engines. The emission of CO represents fuel combustion inefficiency and in aviation, as a consequence of the economic loss such inefficiency creates, there has been sustained pressure to reduce CO emissions by enhancing the fuel economy of aircraft. The direct environmental impacts of carbon monoxide are considered less important than those of NO_x in Europe, although this may not be the case elsewhere, e.g. the United States.

3.2.4 Hydrocarbons

3.2.4.1 Hydrocarbons, or VOCs, are an increasingly important component of air quality concerns relating to amenity and health. The major emission sources in the airport environs are motor vehicle and aircraft emissions, and releases associated with refuelling and fuel storage. Many of these compounds are odorous; indeed the typical airport smell of unburned or partially burnt kerosene is evidence of this. There is a wide range of hydrocarbon species emitted from combustion sources at airports, which includes a number of carcinogenic species. For example, formaldehyde (HCHO) is both directly emitted and formed by photochemical reactions. Aircraft engines have a particularly high emission index for HCHO, in comparison to other combustion sources.

3.2.5 Particulate matter

3.2.5.1 Particulate matter is not a single pollutant but can have varying chemical composition in many different particle sizes and originate from a wide range of natural and man-made sources. The

term 'PM_{10}' is used for particulate matter that has an aerodynamic diameter of less than 10 μm. Airborne PM_{10} can be further divided into course and fine fractions. However, the terminology is fraught with difficulties: 'fine particles' is often used in an atmospheric science context of meaning sub-micron, whereas in air quality management terms (i.e. the regulatory perspective), 'fine' is operationally defined by particular measurements, meaning < 2.5 μm. Within the airport environs, the major source of fine particles is fossil fuel combustion i.e. road vehicles, aircraft and stationary plant. In terms of particles from aircraft engines, these divide into two types, soot (mainly carbon) and volatile particles. The volatile particles are thought to arise from condensed sulphuric acid and possibly condensable organic species. Aircraft engines do not emit any significant amounts of 'coarse' particles, and these typically are composed of oxides of crustal elements and are mainly fugitive dust from roads, industry and construction activity.

3.3 Airport sources

3.3.1 Emissions from airports can be categorized according to the following broad source groups including those identified below. For a detailed description and tutorial on calculating gaseous emissions from airport sources the reader is directed to the US FAA web site: http://www.aee.faa.gov/aee-100/aee-120/aqp/aqp1.htm, which provides a comprehensive handbook on calculating emissions from civilian airports.

3.3.2 Aircraft

3.3.2.1 Emissions from aircraft are primarily confined to the process of fuel combustion by aero engines and auxiliary power units. The magnitude of emissions from aero engines is largely dependent upon load. Low load settings are synonymous with engine inefficiency and are primarily characterized by emissions of CO and HCs. Higher load settings, such as during take-off and climb out, are associated with the optimization of engine performance, and are generally characterized by emissions of NO_x, through the oxidation of atmospheric N. Emissions during the whole of the LTO cycle are generally assumed to form part of the pollution burden associated with airports (Figure 3-2). However, it should be acknowledged that the times in mode promulgated by ICAO (ICAO 1993)[46] are not particularly representative of how aircraft are operated. For further information on how aircraft are operated within the LTO cycle the reader is directed to the findings of Bjornstom *et al.* (2001)[3][47]. Emissions from auxiliary power units (APU) can also be significant

[3] http://www.nlr.nl/public/hosted-sites/aerocert/ACframes.htm

and are largely dependent upon a number of factors including length of use and load factor (Webb, 1995)[48].

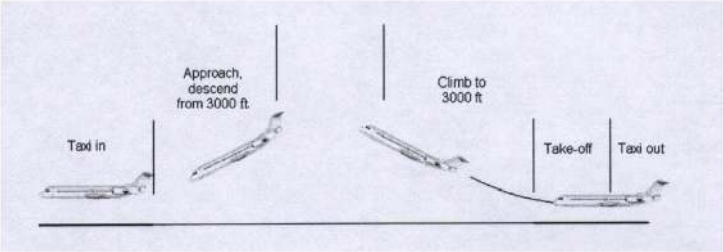


Figure 3-2 The landing/takeoff cycle

3.3.3 Airside vehicles and ground support equipment

3.3.3.1 Airside vehicles are potentially a major emission category within airports. Such vehicles include e.g., tugs, coaches, tankers, catering trucks and baggage trolleys. The operation of these vehicles is often characterized by relatively small distances travelled at low speeds and long periods of use. Emissions from such vehicles typically contribute 5–10 % of total airport NO_x. Ground support equipment includes for example mobile generators, and air start compressors.

3.3.4 Landside vehicles

3.3.4.1 This category of emission sources includes all road vehicle movements outside the airport operational area. Vehicles include cars, taxis, coaches, HGV, LGV, light rail and heavy rail. All the sub-categories of landside vehicles have emissions profiles and the strength of the source is dependent upon many factors including size of engine, speed and duration of use. Typically, emissions from landside vehicles on roads within the immediate airport environs (e.g. access roads and car parks) contribute about 10% to the airport NO_x budget.

3.3.5 Stationary power generation

3.3.5.1 Airports generally will own and operate a number of power generation plants that are typically fuelled by gas or diesel. These sources can have a local importance and may for example contribute in the order of up to 5% of the total NO_x budget

3.3.6 Minor sources

3.3.6.1 There are a number of minor sources within airport environs that emit a wide range of pollutants; these include fire training exercises, aircraft maintenance and engine testing and de-icing (glycol has a number of pathways into the environment). Fuel storage and handling can be a significant source of hydrocarbon emissions at an airport. Emissions are generally categorized as working and handling losses.

3.4 Ambient air quality at airports

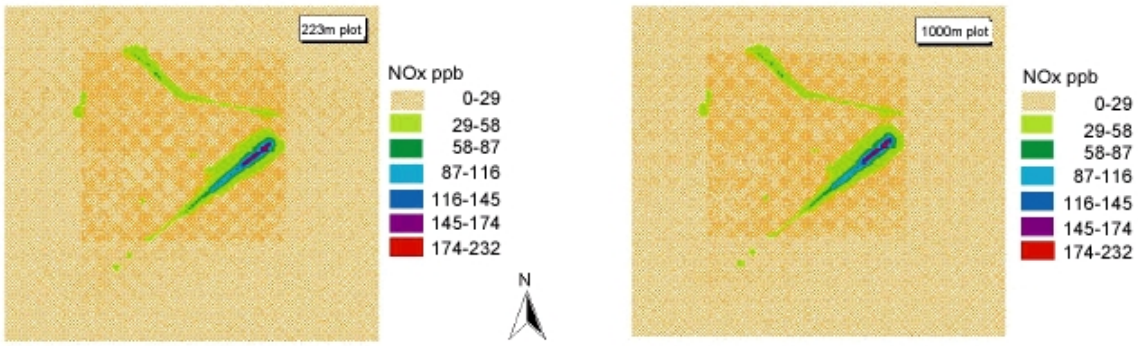
3.4.1 Ambient air quality monitoring data collected at sites within and close to airports generally suggests that pollutant concentrations are similar to, or even lower, than the urban areas they serve. Typically, monitoring data show compliance with standards prescribed in the European Framework Directive and in the UK the National Air Quality Standards except for possibly NO_2 at some of the largest airports (e.g. Heathrow). However, due caution should be used in reviewing air quality data from monitoring sites and attention should be paid to location, proximity and strengths of emission sources.

3.4.2 Air quality at airports is influenced by emissions from a range of sources – local, regional, national and transboundary (Lindley *et al*., 1999)[49]. Determination of the relative contribution of such sources within an airport can only be achieved by modelling (Owen *et al*., 1999)[50]. Figures 3-3a and 3-3b show the modelled impact of airport NO_x sources on local air quality at Manchester Airport for 1999 (before the second runway was opened). Figure 3-3a only considers aircraft emissions from the ground up to 200 m and Figure 3-3b considers aircraft emissions up to 1000 m. It is interesting to note that local ground level impacts of NO_x from aircraft emissions is not particularly sensitive to emissions above a height of about 200 m. This observation has been described by others, e.g. Wayson and Fleming (2000)[51]. Consequently, although it is conventional to calculate and report emissions attributable to airports for all stages of the LTO cycle, e.g. aircraft operations up to 3,000 feet (~1000 m) only a proportion of these emissions, particularly NO_x, have an impact on *local* air quality.

3.4.3 However, the modelling of aircraft emissions on local air quality is at a relatively primitive stage. Conventional small-scale models are usually of a Gaussian structure, which determines dispersion under specified meteorological conditions (see Pasquill and Smith, 1983)[52]. Whether the Gaussian approach is adequate is an open issue, as such models were originally developed to represent point sources and line sources, not complex 3D emission sources such as an airport. Unfortunately, there is little active research and development in this area and whilst airports and

regulators have an urgent need for an 'off-the-shelf' modelling solution, although some are available, they have significant shortcomings. For example, most such models do not represent atmospheric chemistry, being simple passive tracer dispersion model. Given that a large fraction of the direct emission is NO, not NO_2, the NO to NO_2 conversion is oxidant limited and dispersion models are worst-case, assuming complete instantaneous conversion to NO_2. Whilst such an assumption might be 'precautionary' it will not suit all stakeholders, nor is it good science. Oxidant limitation was found in the vicinity of Frankfurt Airport by Jung (2000)[53], who used a complex Lagrangian model, which included a good description of atmospheric chemistry. Moreover, Jung's simulations also showed a small increase of O_3 *and* NO_2 at some distance from the airport as a consequence of the airport's emissions.

3.4.4 Thus, modelling airport and aircraft emissions for the determination of air quality can be shown to be a complex issue, requiring consideration of pollutant contributions beyond the near vicinity of the airport.



a b

Figure 3-3 Predicted annual average NO_x concentrations associated with emissions from all sources at Manchester Airport - including aircraft emissions to 223 m (a) and 1000 m (b)

3.4.5 Airports are generally located on urban fringes and are usually large intermodal transport hubs. Therefore, it is reasonable to expect that emissions from a wide range of sources contribute to local air quality. Figure 3-4 illustrates the predicted NO_x concentrations within the local environs of Manchester Airport, during 1999, when all sources within Greater Manchester and North Cheshire are considered in the simulation. This exercise clearly illustrates the importance of sources external to the operation of the airports on local air quality.

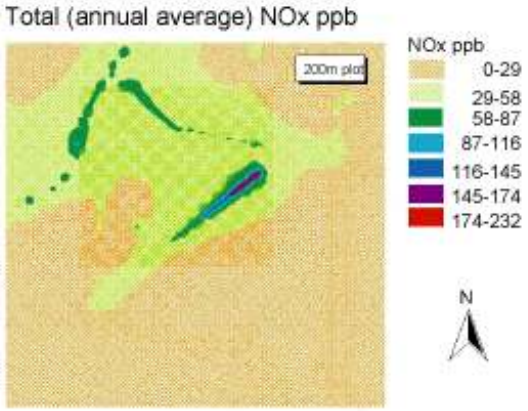


Figure 3-4 Predicted annual average NO_x concentrations associated with emissions from all sources at Manchester Airport - including aircraft emissions to 200m and sources within Greater Manchester and North Cheshire

3.4.6 Within communities in close juxtaposition to airports, air quality issues are frequently manifested by complaints to the airports authority about odour or oil spotting. A frequent misconception is the association of aircraft fuel dumping or venting with the natural formation of contrails under certain weather conditions. The community response to local air quality is complex and difficult to disentangle from other issues such as noise disturbance and third party risk, and is beyond the scope of this paper. However, for airport authorities, all environmental complaints are important but it is interesting to note that Manchester Airport receives about 5000 – 6000 noise complaints per annum and only 20 air quality complaints; similarly Düsseldorf Airport received approximately 3000 noise complaints in the year 2000 and only 10 odour complaints.

3.4.7 Aircraft, as sources, are not regulated as such. The ICAO emission limits are manufacturing standards to ensure engines achieve regulatory compliance and do not reflect the normal *monitored* emissions of other sources subject to environmental regulations. Nonetheless, if ambient air quality standards are breached, then the onus is upon the Local Authority (in the UK) to determine what source is responsible and to take appropriate action. As airport growth continues, then there is the real possibility that local air quality standards may represent a constraint to growth. This concern is reflected in the ICAO emission limits, which are constantly under review.

4 EFFECTS ON THE GLOBAL ATMOSPHERE

4.1 Characteristics of the global atmosphere

4.1.1 The atmosphere below 50 km (see Figure 4-1) can be characterized by two distinct regions: the troposphere and the stratosphere, which are separated by the tropopause at roughly 10 km. The temperature structure and composition of these regions depends on chemistry, radiation and dynamics as well as emissions.

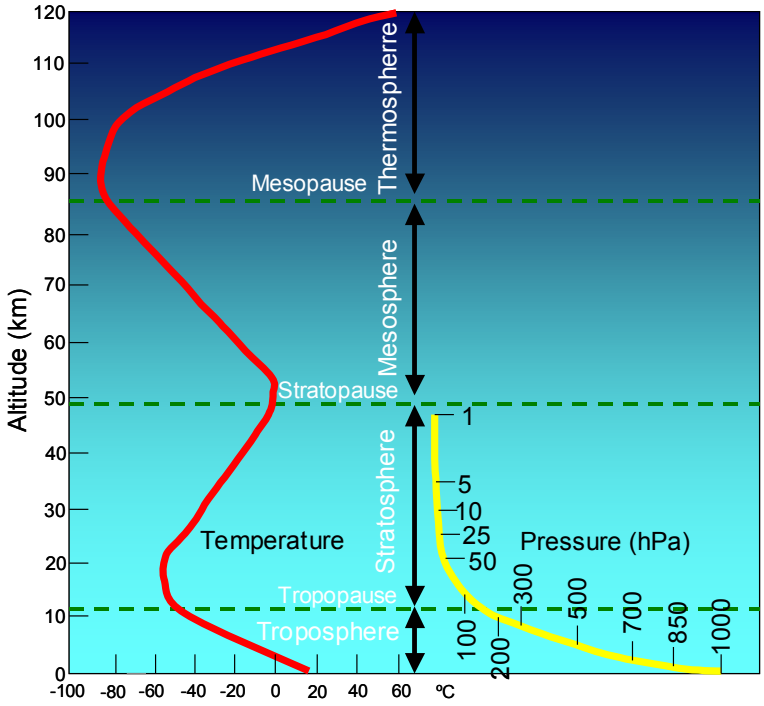


Figure 4-1 Generalized temperature and pressure structure of the atmosphere by height

4.1.2 The troposphere (approximately 0 to 10 km altitude) is rich in water vapour and poor in O_3, with O_3 chemistry dependent upon the levels of NO_x and HCs. Vertical transport, associated with mid-latitude weather systems and convection, is more rapid in the troposphere than in the stratosphere. Since the early 1900s O_3 in the troposphere has more than doubled (Staehelin *et al.*, 2001)[54]. This is almost certainly a result of increasing emissions of gases, such as NOx and CO, which are largely produced by human activities (e.g. vehicles, power stations and aircraft) (see Section 2.3).

4.1.3 In contrast, the stratosphere (approximately 10 to 50 km altitude) can be characterized as a region of slow vertical transport, rich in O_3 and poor in water vapour, with O_3 loss chemistry dominated by catalytic destruction cycles (WMO, 1999)[55]. Above the tropopause, convection is inhibited as the temperature of the stratosphere generally increases with altitude. This increase in temperature is a result of the radiative energy budget of the stratosphere, and is caused by shortwave heating, due to O_3 absorption. The thermal structure, and indirectly the dynamics, is therefore dependent upon the concentration of O_3. Observations from satellites and balloons have revealed that O_3 concentrations have dramatically decreased in the polar stratosphere since the early 1980s (e.g. SORG, 1996[56]; 1999[57]). This is almost certainly because of the presence of man-made chlorine and bromine compounds in the atmosphere.

4.1.4 In determining the general circulation of the atmosphere (see Figure 4-2), the behaviour of long-lived atmospheric constituents was examined by Dobson (1930)[58] and Brewer (1949)[59]. These observations revealed a general upwelling of air in the tropics, where tropospheric air enters the stratosphere, and downwelling at middle and high latitudes, which results in the high values of O_3 found in the extratropical lower stratosphere. Conservation of mass is maintained by the gradual movement of air poleward in the stratosphere. This circulation of air is responsible for the observed distribution of O_3 and other chemical species and is referred to as the *Brewer-Dobson circulation*. A review of the discovery and description of the stratosphere is given by Labitzke and van Loon (1999)[60].

4.1.5 The composition of the atmosphere is dominated by nitrogen (N_2) and oxygen (O_2), representing 99% of the volume of dry air. However, the chemistry of the atmosphere is dominated by, relatively speaking, small concentrations of various reactive species. In terms of the overall chemistry of the atmosphere, it is an oxidizing environment, dominated by thermal and photolytic reactions. The trace chemical species introduced to the atmosphere can have lifetimes ranging from fractions of a second to millions of years, depending upon the physical and/or chemical removal processes that pertain to them (see examples in Table 4-1). Many of these species have distinct global biogeochemical cycles, some of which are only very poorly understood. In terms of species that are radiatively active, or have perturbed the stratospheric O_3 layer, man-made sources of various chemical species have often perturbed the relevant biogeochemical cycles, or introduced non-naturally occurring species. Simple summaries of the controlling features of the chemistry of the troposphere and the stratosphere are given in Boxes 2, 3 and 4.

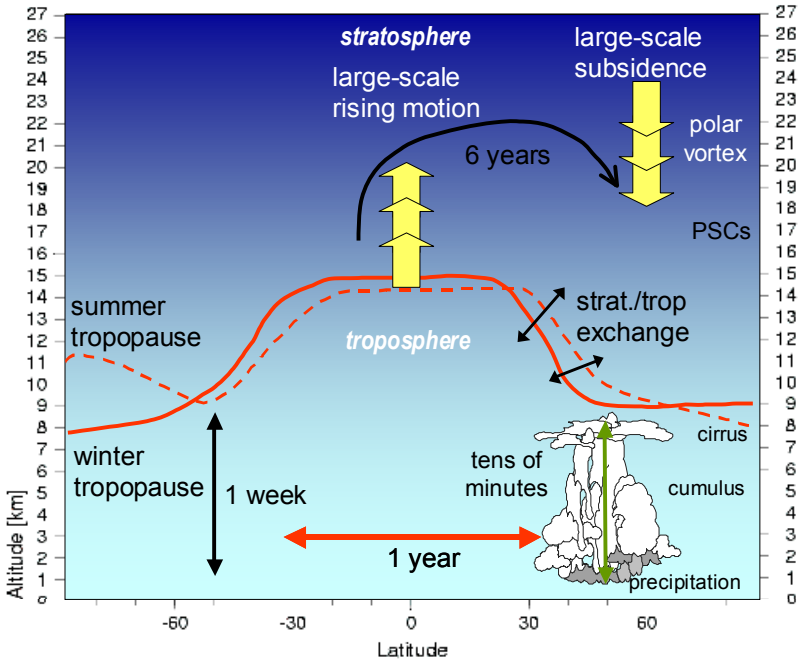


Figure 4-2 Latitudinal representation of the general circulation of the troposphere and stratosphere indicating transfer timescales: inter-hemispheric: 1 year; surface to tropopause: 1 week; convective venting of planetary boundary layer to free troposphere: tens of minutes; stratospheric circulation: 6 years

4.1.6 In terms of aircraft emissions of the current subsonic fleet, and their effects on chemical composition, these are injected into a particularly complex region of the earth's atmosphere, the upper troposphere and lower stratosphere (UT/LS). New insights into the dynamics of the UT/LS region between 6 and 20 km, combined with an increase in constituent measurements, have resulted in a better understanding of the structure and composition of this region. It is no longer satisfactory to think of the tropopause as a sharp boundary. New measurements have shown that the composition of the UT/LS region has, on different occasions, characteristics of either the troposphere, stratosphere, or a mixture of both. Accordingly, the dominant chemical processes in this region are not necessarily those normally associated with either the stratosphere or the troposphere. This complexity means that predicting the temporal evolution of composition is conceptually more difficult than previously thought.

Table 4-1 Mean concentration of selected gases in the troposphere and their typical lifetimes (source: compiled from Brasseur et al., 1998[10]; Seinfeld and Pandis, 1998[61])

Species	Formula	Volume mixing ratio	Lifetime†
Nitrogen	N_2	0.781	1.5×10^7 yr
Oxygen	O_2	0.209	4000 yr
Carbon dioxide	CO_2	355 ppm	50–200 yr
Methane	CH_4	1.73 ppm	8–10 yr
Hydrogen	H_2	0.58 ppm	
Ozone	O_3	5–50 ppb (surface)	week
		100 ppb (tropopause)	months
Carbon monoxide	CO	50–200 ppb (surface)	8 weeks
		50–100 ppb (tropopause)	3 weeks
Nitrous oxide	N_2O	313 ppb	130 yr
Nitrogen oxides	NO_x ($NO + NO_2$)	0.01–1 ppb (surface)	days
		0.05–0.5 ppb (tropopause)	weeks
Water	H_2O	(surface)	days
		10 ppm (tropopause)	weeks
Hydroxyl radical	OH	35 ppt	1–5 s
Hydroperoxy radical	HO_2	170 ppt	10 s

† the lifetime of many of the shorter-lived species, is highly dependent on local conditions, from emissions or the presence of other gases.

4.2 Aircraft, climate and the concept of radiative forcing

4.2.1 For over 100 years it has been known that the natural 'greenhouse effect' of water vapour and carbon dioxide in the Earth's atmosphere keep its surface temperature some 34 ºC warmer than it would otherwise be (IPCC, 1995)[62]. As a result of industrialization there has been an undisputed 36% rise in levels of carbon dioxide (CO_2) over the last 150 years, which is expected to have led to an increase in the Earth's temperature. This science is based on increases in CO_2 perturbing the Earth's energy balance by trapping (absorbing and re-emitting) more of the outgoing terrestrial radiation. For CO_2, this absorption can be measured in the laboratory and recently a study of historic satellite data has, for the first time, detected a change in the outgoing terrestrial radiation during 1970-1997 (i.e. a perturbation to the Earth's energy balance) which is directly attributable to the CO_2 increases (Harries *et al*., 2001)[63].

4.2.2 Despite this understanding in the role of CO_2 there are still large uncertainties in attempting to attribute the 0.6 ± 0.2 ºC increase in the globally averaged temperature over the last 100 years (e.g. IPCC, 2001)[64] to a human cause and predict future temperature changes. Two of the largest sources of uncertainty arise from an incomplete knowledge of the various feedbacks in the Earth-Atmosphere system (see Section 5) and uncertainties in the quantification of the other climate change mechanisms.

4.2.3 Assessing the role of aircraft is a good example of the difficult but important task that is faced in predicting future climate change. Given that much recent discussion has focussed upon the estimates of radiative forcing from aircraft effects given by IPCC (1999)[6] for 1992 and 2050, it is pertinent to introduce some of the basic concepts of climate change. In Section 5, the details of aircraft effects on climate are dealt with in more detail.

4.2.4 'Climate' is, of course, different from 'weather'; weather being the more-or-less instantaneous meteorological conditions whereas climate describes weather conditions typical of a region or site (e.g. McIlveen, 1992)[65]. Climate *change* is a long-term systematic change of climate, usually measured by surface temperature. However, as it is extremely difficult to simulate or predict changes in surface temperature except with highly sophisticated three-dimensional climate models (for an overview, see McGuffie and Henderson-Sellers, 1997[66]; IPCC, 1997[67]) other quantities are used to compare climate-change mechanisms (see below). Climate change negotiations take place under the aegis of the United Nations Framework Convention on Climate Change (UNFCCC). In order to provide authoritative international statements of scientific opinion on climate change, the World Meteorological Organization and the United Nations Environment Programme jointly established the Intergovernmental Panel on Climate Change (IPCC). The IPCC has delivered major reports on the science of climate change in 1990[68], 1995[62] and 2001[64].

4.2.5 In order to quantify effects of radiatively active gas emissions, the concepts of 'Global Warming Potentials' (GWPs) and radiative forcing are widely used (e.g. IPCC, 1990)[68]. The Global Warming Potential is an index that allows the climate effects of emissions to be compared, relative to those of e.g. CO_2. They are a measure of the relative radiative effect of a gas or substance integrated over a specified time horizon (e.g. 20, 100 and 500 years in IPCC, 2001)[64] - see Box 1. Global Warming Potentials are suitable for long-lived gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the halocarbons. For shorter-lived gases, their usage is more problematic. The usage of GWPs for indirect effects, such as NO_x emission on O_3 production, is difficult because, for example O_3 production and abundance is dependent on atmospheric chemistry, the background atmosphere and other physical conditions. For shorter-lived species and indirect effects that are difficult to quantify via GWPs the related concept of radiative forcing is usually employed to compare competing effects.

4.2.6 Radiative forcing may be defined as a measure of the importance of perturbations to the planetary radiation balance and is measured in Watts per square metre (W m^{-2}). One of the main reasons for its use as a convenient metric is that there is an approximately linear relationship between the change in global mean radiative forcing (ΔF) and the global mean surface temperature change (ΔT_s), i.e.:

$$\Delta T_s \approx \lambda \Delta F \quad (1)$$

4.2.7 where λ is the climate sensitivity parameter (K (W m^{-2})$^{-1}$) (e.g. Shine and Forster, 1999)[69].

4.2.8 It is worthwhile putting values of radiative forcing in context. Figure 4-3 summarizes the energy balance of the earth's atmosphere system. This shows that incoming and outgoing radiation is balanced (as a global average) at 240 W m^{-2}. Climate change in UNFCCC usage refers to perturbations of climate from human activities, either directly or indirectly, and is that in addition to natural climate change.

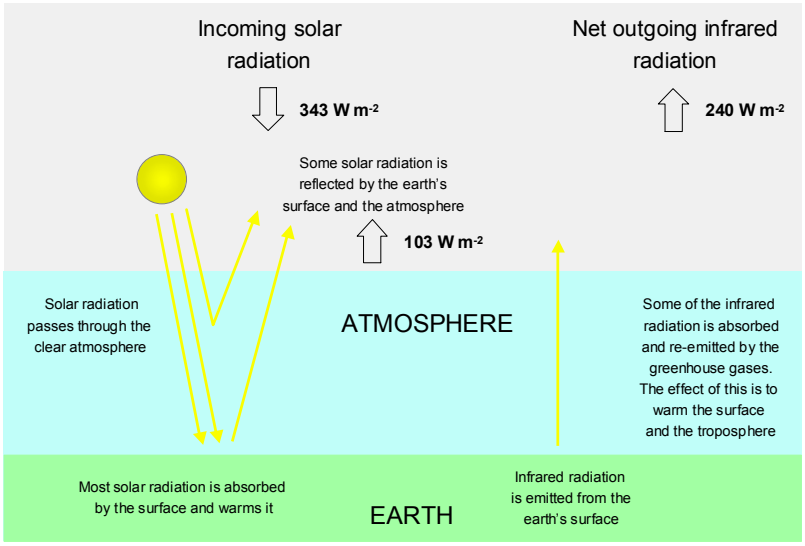


Figure 4-3 The Radiative Energy Balance of the Earth's Atmosphere

4.2.9 The recent Summary for Policymakers of the Third Assessment Report (SPM–TAR) of the IPCC, Working Group 1 (IPCC, 2001)[64] provides the most up-to-date assessment of radiative forcing of climate that may be conveniently given in one figure, shown in Figure 4-4.

4.2.10 This figure shows the radiative forcing from different components: the aircraft 'contrails' and 'enhanced cloudiness' are simply picked out as they are signatures unique to aviation, other aviation effects being subsumed into the other radiative forcing bars. It is incorrect to simply sum the radiative forcing values because of shorter or longer lasting effects. The radiative forcings are from a number of agents since 1750, expressed as global annual means. Some species are more long-lived than others; thus, if emissions of a long-lived species stopped tomorrow, the effect would continue for centuries. Other effects, such as that of sulphate aerosol would cease within approximately one or two months under the same hypothetical scenario of the complete cessation of emissions. Nonetheless, it is useful to point out a total radiative forcing of approximately 2.5 W m^{-2} from the long-lived greenhouse gases in the first bar (i.e. CO_2, CH_4, N_2O, CFCs). It should therefore be appreciated that relatively small perturbations can make measurable and significant impacts on climate. It also needs to be remembered that aircraft radiative forcings have grown over a far shorter timescale than those from other sources, so such a figure showing integrated changes since 1750 somewhat downplays the role of aircraft.

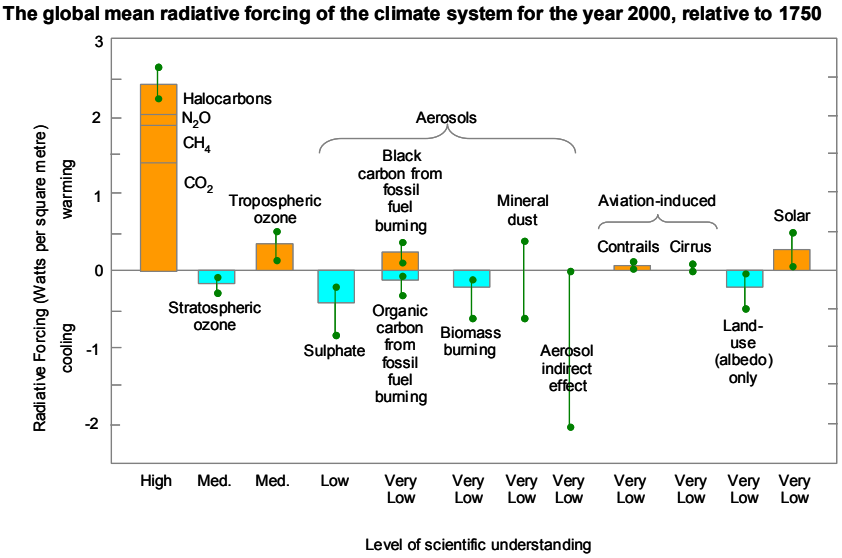


Figure 4-4 Global Annual Mean Radiative Forcings (W m^{-2}) from a Number of Agents for the Period from the Pre-industrial (1750) to the Present (2000). Source: IPCC (2001)

4.2.11 Before moving on to estimates of radiative forcing from aviation, it is worth considering the question of what this total perturbation of climate means. The SPM-TAR states that the increase in

global average surface temperature over the 20th Century was 0.6 ± 0.2 ºC. From a range of emissions scenarios and model assessments, globally averaged surface temperature is projected to further increase by between 1.4 to 5.8 ºC from 1990 to 2100, for a range of scenarios.

4.2.12 Having set the scene with the overall influences on climate and radiative forcing, we move on to illustrate the effects of subsonic aviation in 1992 and 2050, as estimated by the IPCC (1999)[6] and shown in Figure 4-5. Here, we see an overall forcing of 0.05 W m^{-2} in 1992, approximately 3.5% of the overall radiative forcing (as estimated in the IPCC's Second Assessment Report: IPCC, 1996)[35], and an overall forcing of 0.19 W m^{-2} in 2050, 5% of all climate forcings for a central scenario. The full range of 2050 scenarios studied imply forcings of 0.13 to 0.56 W m^{-2}, i.e. 2.6 to 11 times the value in 1992. Figure 4-5 shows the large uncertainties associated with contrail and cirrus effects (the two being linked) the latter having no best estimate associated with it.

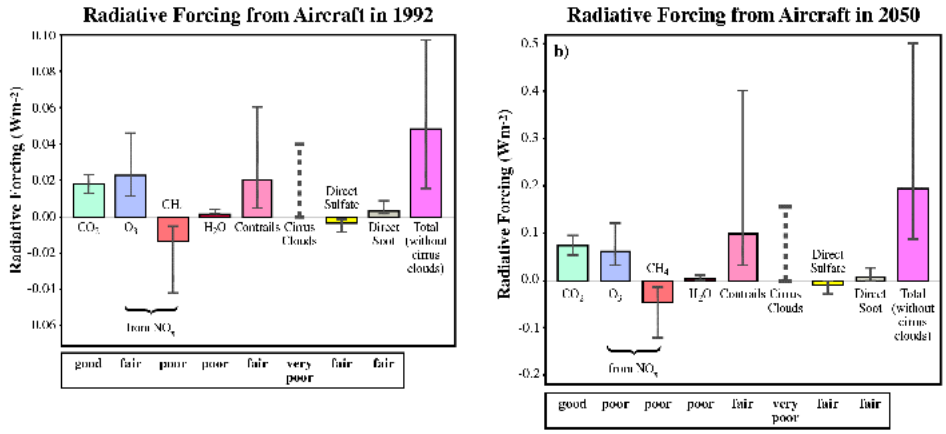


Figure 4-5 Global Annual Mean Radiative Forcings from Aircraft Emissions for 1992 (a) and 2050, scenario Fa1 (b) (W m^{-2}). Source: IPCC (1999)[6] and DLR web-site

4.2.13 Chemical effects of subsonic aircraft on the global atmosphere

4.2.14 Emissions of NO_x result in the catalytic production of tropospheric O_3 via a number of complex chemical processes (see Boxes 2 and 3). Essentially, oxidation of methane (CH_4), carbon monoxide (CO) and non-methane hydrocarbons (NMHCs) results in the production of the peroxy radicals (RO_2). This RO_2 then reacts with NO to form NO_2, which may subsequently photodissociate, re-forming NO and liberating the highly reactive atomic oxygen (O). Atomic oxygen reacts with O_2, forming O_3. This chemical process occurs in the natural atmosphere but the introduction

of extra NO_x catalytically enhances the production rate of O_3. This is summarized in Figure 4-6, in which the catalytic role of NO_x is shown, forming and recycling OH and RO_2.

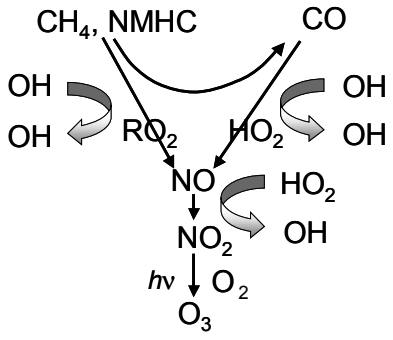


Figure 4-6 Representation of the Production of Ozone from Methane, Carbon Monoxide and Non-Methane Hydrocarbons

4.2.15 The production of O_3 at altitudes at which subsonic aircraft typically fly (10–12 km) is rather efficient and it is not so readily removed from the atmosphere as at the ground, and thus has a residence time of weeks to months. Moreover, due to variations of ozone and temperature with altitude, the surface temperature response for a change in O_3 is altitudinally dependent, as show in Figure 4-7.

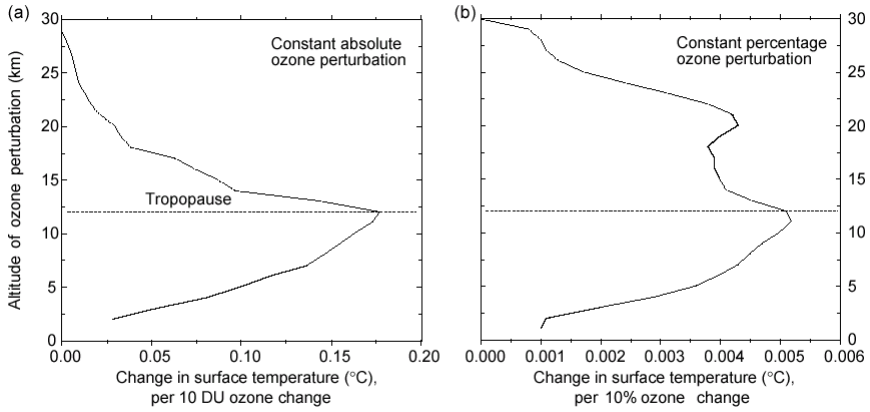


Figure 4-7 Dependence of the surface temperature response on the height and type of O_3 perturbation; (a) shows the sensitivity to a constant absolute change (10 DU), while (b) shows the sensitivity to a constant percentage change (10%). From Forster and Shine (1997)[70]

4.2.16 Using 3D inventories of aircraft emissions, such as that shown in Figure 2-1, it is possible with a 3D chemical transport model (CTM) of the global atmosphere to calculate the perturbation induced by aircraft. Such a model typically divides the global atmosphere into grid-boxes in three-dimensional space; wind-fields from global climate models are used with a typical time interval of 6 hours to transport the source gases around, over which period chemical reactions are calculated over shorter time-periods, typically 5 to 30 minutes. Such a model is described as 'off-line' as the chemical perturbations modelled do not feed back on atmospheric dynamics. More advanced 'fully-coupled' models are being developed, which meld a simplified description of the chemistry of the atmosphere within a global climate model (e.g. Hein *et al*., 2001)[71] but these are in their infancy. In practice, either CTMs or combined CTM/GCMs tend to be a compromise of either physical effects (coupling) or complexity of chemistry because of the vast computational resources required to run such models.

4.2.17 Perturbations attributable to aviation NO_x emissions and the resultant O_3 formed are shown from our own modelling studies in Figures 4-8a and 4-8b (Lee and Raper, 2002)[72]. These figures show the enhancement of NO_2 and O_3 for 1992 emissions and a sample 2050 scenario at cruise altitudes for July conditions using a simplified description of tropospheric chemistry (the NO_x–HO_x–CO–CH_4–O_3 system). The NO_2 concentrations, unsurprisingly, show a marked resemblance to the pattern of NO_x emissions, with some smoothing. By contrast, the O_3 perturbation shows a much more 'smeared out' pattern, varying across the Northern Hemisphere where much of the emissions occur, with tongues of ozone being transported across the hemispheres because of the long residence time.

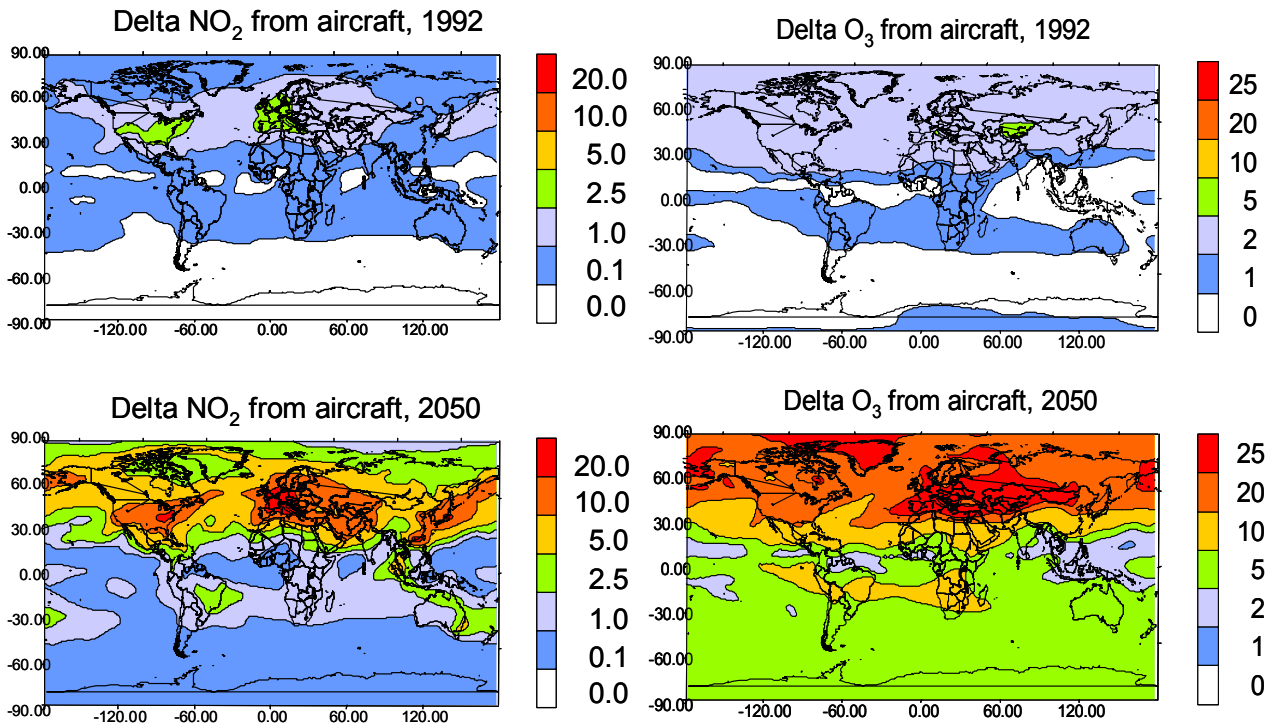


Figure 4-8 Modelled nitrogen dioxide concentrations in ppt (a) and ozone in ppb (b) from aircraft at cruise altitudes for 1992 and a 2050 scenario (Fe1)

4.2.18 Ozone chemistry in the troposphere has been shown in modelling studies to be non-linear (e.g. Grooß *et al*., 1998)[73], i.e. with addition of NO_x over a critical concentration, O_3 production actually decreases. In field measurements, however, this theoretical relationship has been elusive, although careful analyses of *in situ* data have shown an approach of NO_x-saturated conditions over the North Atlantic (Jaeglé *et al*., 1999)[74]. However, in common with other global model studies (e.g. Chapter 2 IPCC, 1999[6]; Grewe *et al*., 1999[75]), we have found that increases in global aircraft NO_x emissions result in an apparently linear increase in global O_3 (Figure 4-9a). However, if the data are plotted for different regions, different responses are shown (Figure 4-9b). In the Southern Hemisphere (i.e. 90°S to 20°S), where NO_x concentrations are currently rather low, O_3 production increases much more strongly than in the tropics, or in northerly latitudes because of the non-linearity of the chemistry.

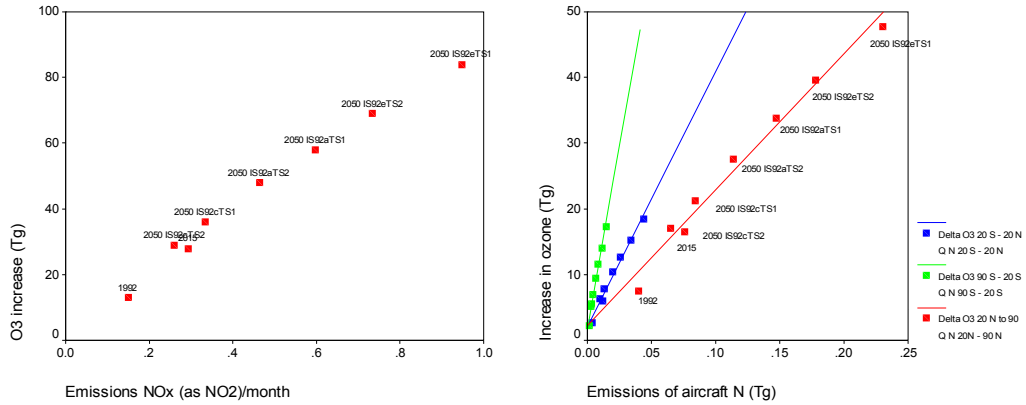


Figure 4-9 Global increase in O_3 inventory for June conditions vs increase in aircraft NO_x emissions under various scenarios (a) and regional increases in O_3 inventory for June conditions vs. increase in aircraft NO_x emissions under various scenarios—green indicates latitudes 90°S to 20°S; blue indicates 20°S to 20°N; red indicates 20°N to 90°N (b)

4.2.19 From similar simulations undertaken for the IPCC (1999)[6] report (see Chapter 4 of IPCC, 1999)[6], it was found that the aircraft NO_x emissions resulted in a chain of chemical reactions that reduced ambient concentrations of methane (CH_4), which is emitted from other sources; CH_4 being a greenhouse gas. This effect is rather complex and the magnitude of it was something of a surprise, as previous simulations with 2D chemical models of the atmosphere (latitude by height) had demonstrated this effect but at a much smaller magnitude (e.g. Fuglestvedt *et al*., 1996)[76]. Essentially, aircraft NO_x emissions result in an enhancement of OH concentrations, which then reduce CH_4 concentrations via several chemical reactions and transport processes. Thus, aircraft NO_x emissions ultimately result in an enhancement of O_3 in the source regions–primarily the Northern Hemisphere–and an almost even reduction in CH_4 concentrations across both hemispheres. The enhancement of O_3 results in a positive globally averaged radiative forcing and a reduction in radiative forcing from reduced CH_4 concentrations (reduced by approximately 2–4%).

4.2.20 That the globally averaged O_3 radiative forcing has an approximately equal and opposite magnitude to the reduction of CH_4 radiative forcing has resulted in the erroneous conclusion in many quarters that there is no climate effect (e.g. Ewins, 2000)[77]; despite the fact that the IPCC report clearly stated otherwise (IPCC, 1999, Section 6.5.1)[6]. It would be more correct to postulate a partial cancellation of the CO_2 radiative forcing induced by aircraft as at least both CO_2 and CH_4 are more or less well mixed across the hemispheres because of long atmospheric lifetimes. This is a theme picked up in the concluding section of this paper.

4.3 Contrail effects of subsonic aircraft on the global atmosphere

4.3.1 One of the impacts of aircraft on climate that has stimulated much interest and recent research is that of contrails and cirrus clouds. Contrails effects on climate were discussed as far back as the late 1960s (e.g. Appleman, 1966[78]; Chagnon, 1981[79]); however, these studies did not receive much attention. The potential effects of contrails were then discussed by Schumann and Wendling (1990)[80] and the efforts made towards the IPCC report really brought this issue to the fore.

4.3.2 Contrails form on particles that are emitted directly from the engine, such as soot and sulphate particles that form in the plume, and perhaps in the engine itself (Tremmel *et al*., 1998[17]; Tremmel and Schumann, 1999[81]). Of this mixture of particles, the particle number density of sulphate particles is approximately 1 to 2 orders of magnitude greater than that of soot particles in the plume (Anderson *et al*., 1998[82]; Schröder *et al*., 1998[83]).

4.3.3 The formation of contrails arises from the increase in relative humidity that occurs during the mixing of the warm and moist exhaust gases from the aircraft engines with the colder and less humid ambient air, which condenses on engine exhaust particles and subsequently freeze. A contrail forms when saturation with respect to liquid water is reached or surpassed in the plume. For contrails to be persistent, the air mass through which the aircraft flies needs to be supersaturated with respect to ice. Thus, the critical factors in persistent contrail formation are: water vapour and particles from the engine exhaust; and particular conditions of temperature and humidity. In effect, since the engine exhaust conditions are not so variable, it is the environmental parameters that dictate whether a persistent contrail will form or not. Reviews of contrail formation and their dependencies have been provided by Schumann (1996)[84], Kärcher (1999)[85], and IPCC (1999, Chapter 3)[6].

4.3.4 The review and synthesis efforts associated with the IPCC report showed that the radiative effects of persistent contrails and the enhancement of cirrus cloudiness were potentially large (see Figure 4-5). Sausen *et al*. (1998)[86] computed potential persistent contrail coverage for 1991/92 and Gierens *et al*. (1999)[87] for 2050. These coverages were utilized by Minnis *et al*. (1999)[88] to calculate radiative forcing using a simple radiative transfer model for these two time-lines. The globally averaged radiative forcing from line-shaped contrails was shown to be ~0.02 W m^{-2} in 1992 and ~0.1 W m^{-2} in 2050 for the central Fa1 scenario (Minnis *et al*.,1999)[88].

4.3.5 The other issue associated with contrails is the enhancement of cirrus clouds. Cirrus clouds can have a powerful effect on surface temperatures (Liou, 1986[89]; Lohmann and Roeckner, 1995[90]) and are a major source of uncertainty on global climate modelling studies. The above-mentioned

estimation of radiative forcing is for line-shaped persistent contrails only. Persistent contrails may spread by diffusion and wind-shear to give a cirrus-like cloud coverage that cannot be ultimately recognized as have originating from contrails. Moreover, contrails and cirrus clouds (in common with all clouds) must nucleate on particles, typically sub-micron in size, Aircraft introduce such particles from soot and sulphate particles in the plume. It is possible that these condensation nuclei can trigger cirrus cloud formation long after the aircraft has passed, perhaps when temperature and ice-supersaturation conditions are more favourable for cirrus formation.

4.3.6 Boucher (1999)[91] showed a correlation between increases of air traffic in the North Atlantic Flight Corridor (NAFC) and increases in cirrus cloud coverage. A possible relationship between the two was postulated but it was acknowledged that other causes could be contributory. Extending analyses of possible cirrus cloud increases, IPCC (1999, Chapter 3)[6] concluded that "*...a possible relationship between air traffic and cirrus formation*" may exist.

4.3.7 However, the uncertainties were so large in the IPCC's analysis that a best estimate of radiative forcing could not be given, only an uncertainty estimate that ranged from 0 (no effect) through to ~0.04 W m^{-2} for 1992.

4.3.8 There are several major sources of uncertainty in the radiative forcing estimates for line-shaped persistent contrails and enhanced cirrus cloudiness: contrail coverage calculations, optical depths of the clouds and ice crystal size distributions are all critical factors (Lee *et al*., 2000)[92].

4.3.9 More recently, two different estimations of contrail radiative forcing have been made. The first, by Ponater *et al.* (2001)[93] utilized a revised estimation of contrail coverage and found a smaller radiative forcing—this is discussed in more detail in Section 5.2.

4.4 Effects of supersonic aircraft on the global atmosphere

4.4.1 It has been suggested over the past 30 years or so that a significant fleet of supersonic transports (SSTs) would become economically and technically feasible. Most recently, the NASA High Speed Civil Transport (HSCT) research programme investigated technological and environmental possibilities and constraints. Ambitious technological goals were set in the HSCT programme, including an overall $EINO_x$ of 5, based on the supposition that the principal environmental effect would be stratospheric O_3 depletion via NO_x chemistry.

4.4.2 Any injection of trace species from aircraft into the stratosphere has the consequence that their residence time is longer than in the troposphere. Subsonic aircraft currently fly in the lower stratosphere for a significant portion of the time at northerly latitudes. Supersonic aircraft (current

or proposed) generally fly rather higher, ~15 to 20 km. At such altitudes, the residence time of emissions will be even longer, of the order of several years.

4.4.3 In an examination of the potential effects on the stratosphere, hypothetical fleet and emissions scenarios were prepared that included different SST fleet sizes (500 and 1000) and SO_2 to particle conversion efficiencies (IPCC, 1999 Chapter 4)[6]. The aircraft were assumed to cruise at altitudes of approximately 17 to 20 km. Although sulphur is only present in fuel at very low concentrations (see Section 2.1), much of it is thought to be converted to SO_2, which subsequently oxidizes to H_2SO_4, forming particles. Heterogeneous chemistry on these aerosol particles is highly dependent upon the surface area density. As such, future SO_2 emissions from a supersonic fleet may increase the surface area density and therefore possibly lead to further O_3 loss via heterogeneous processes (Hofmann, 1990)[94].

4.4.4 As with subsonic aircraft, emissions of NO_x from supersonic aircraft participate in a wide range of chemical processes in the stratosphere (see boxes 2 and 4). In particular, the primary loss mechanism for O_3 in the middle and upper stratosphere (at altitudes between 30 – 40 km) involves NO_x radicals. Thus, the transport of emissions from supersonic aircraft into the middle and upper stratosphere has a direct effect on the distribution of O_3. In contrast, NO_x radicals in the lowermost stratosphere (at altitudes below 25 km) moderate O_3 loss due to other chemical processes involving the radicals of hydrogen oxides (HO_x), chlorine oxides ClO_x) and bromine oxides (BrO_x). Thus, the addition of emissions in the lower stratosphere can either increase or decrease O_3 in this region, depending upon the relative balance among the radicals. Results from the University of Cambridge 3D stratospheric chemical transport model (SLIMCAT, see Rogers *et al*., 2000[95]), shown in Figure 4-10, reveal the change in O_3 for June 2015 arising from a fleet of 500 supersonic aircraft with an $EINO_x$ of 5. The relative importance of meteorological interannual variability to the overall impact of supersonic aircraft on the atmosphere has been shown by Rogers *et al*. (2000)[95]

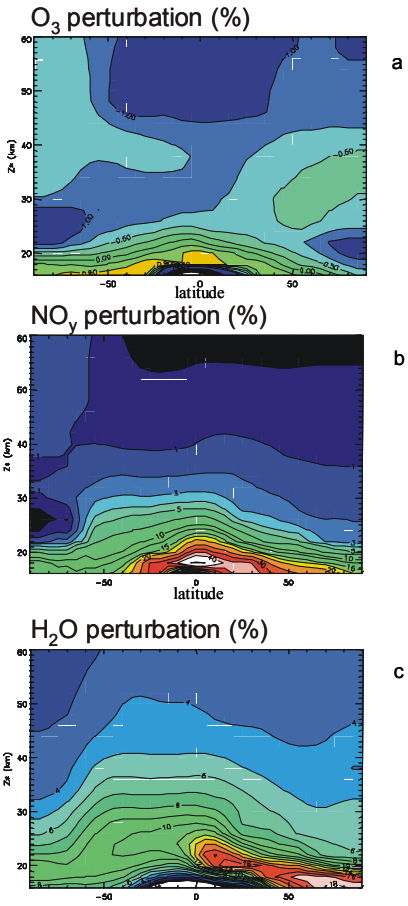


Figure 4-10 Calculated percentage contribution (latitude vs. altitude) of a hypothetical fleet of 500 SSTs (EI-NO_x of 5) to O_3, NO_y and H_2O calculated using the SLIMCAT model

4.4.5 The stratosphere is very dry in comparison to the troposphere and emissions of water vapour from supersonic aircraft injected directly into the stratosphere will have a significant impact. Results from the IPCC (1999) revealed a possible increase in water vapour in the lower stratosphere by about 0.5 ppmv (parts per million by volume), due to a projected fleet of 500 supersonic aircraft. This perturbation equates to a change in water vapour of approximately 10–15%, compared with the background atmosphere (Figure 4-10c). Water vapour is a source of HO_2 radicals in the stratosphere and therefore plays a pivotal role in stratospheric chemical ozone loss processes.

4.4.6 Ozone chemistry in the polar stratosphere is dominated by heterogeneous chemistry on Polar Stratospheric Clouds (PSCs). These PSCs form in the polar atmosphere at heights of 15–25 km where temperatures drop to <195 K during the polar night, allowing the very small concentrations

of water vapour to combine with HNO_3 and/or $H2SO_4$ (Type I PSCs, ~190–195 K threshold of formation) or ice clouds to form (Type II PSCs, ~188–190 K threshold of formation) (see e.g. WMO, 1999)[55]. The microphysical properties of aerosols and PSCs are highly dependent upon the ambient water vapour, HNO_3 and H_2SO_4 concentrations. Both HNO_3 and H_2SO_4 are products of aircraft emissions of NO_X and SO_2 and as such supersonic aircraft may directly affect the occurrence of PSCs during the polar winter. Additional water vapour from supersonic aircraft emissions also increase the heterogeneous reactivity on PSCs and may thus influence the concentrations of radical halogen species. These radicals are responsible for the large seasonal O_3 loss during polar winter, commonly referred to as the 'ozone hole'.

4.4.7 Emissions of sulphur, nitrogen oxides and water vapour therefore impact on the chemical processes in the stratosphere, the microphysical properties of aerosols and the radiative energy budget.

5 EFFECTS OF AIRCRAFT ON GLOBAL CLIMATE

5.1 Quantifying climate impacts

5.1.1 This section introduces ways of assessing climate impact, then goes on to specifically discuss the role of aircraft. Owing to uncertainties in the climate sensitivity (see below) radiative forcing has been used extensively in the IPCC process to compare and contrast different climate change mechanisms (see Section 4.2) and the metric is built into the quota system of the Kyoto Protocol. However, for assessing the effect of aircraft the concept may not be as useful due to: 1) the localized nature of aircraft flights and some of their climatic consequences and 2) the indirect nature of some of the mechanisms involved. For example, it is unclear how to model the indirect effects of aircraft on cirrus clouds using this metric. Despite these difficulties, it is still invaluable in providing a first-order estimate of competing effects (Shine and Forster, 1999)[69].

5.1.2 For small perturbations, climate model experiments (e.g. IPCC, 1995[62]; Hansen *et al*., 1997[96]; Forster *et al.*, 2000[97]) indicate that the equilibrium global-mean surface temperature change (ΔT_s) is approximately linearly related to the change in radiative forcing (ΔF), as discussed in Section 4.2). The value of the climate sensitivity parameter (λ) is governed by a number of feedbacks, including changes in water vapour, sea-ice and clouds. Despite a vast improvement in climate models over the last twenty years the quantification of these feedbacks remain little improved with current estimates for the value of λ ranging between 0.3–1.1 K (W m^{-2})$^{-1}$ (IPCC, 2001). It is this uncertainty in λ that is often used by climate-change sceptics to denounce climate model predictions (e.g. Lindzen *et al.*, 2001)[98].

5.1.3 Early climate model experiments (see IPCC, 1995)[62] found that, provided the radiative forcing was appropriately defined, the value of λ remained roughly constant, irrespective of the forcing mechanism. Hansen *et al*. (1997)[96] found that λ varied by no more than 40% for a wide range of different mechanisms and Forster *et al*. (2000)[97] showed that λ remained constant to within 30% when the geographical location of the radiative forcing was varied.

5.1.4 It is known that in order for λ to remain roughly constant, the radiative forcing needs to be defined as the change in radiative flux at the tropopause *after* allowing stratospheric temperatures to adjust to a new equilibrium (IPCC, 1995)[62]. For stratospheric O_3 depletion this 'stratospheric adjustment' is particularly important, changing the sign of the radiative forcing from positive to negative: i.e. although an instantaneous loss of stratospheric O_3 would let more solar radiation through

to the surface, which would be expected to warm the troposphere, there is also a reduction of the absorption of thermal radiation in the stratosphere, causing it to cool; this reduces the downwards thermal irradiance at the tropopause, leading to a net negative radiative forcing and a tropospheric cooling. Usually, an approximation such as fixed dynamical heating works well at determining the stratospheric temperature response (e.g. Ramaswamy *et al*., 2001)[99], allowing this 'adjusted forcing' to be accurately gauged. This fixed dynamical heating approximation is also a useful way of estimating how different mechanisms affect stratospheric temperatures.

5.2 Role of aircraft

5.2.1 The total radiative forcing of aircraft emissions was estimated by IPCC (1999)[6] to be 0.05 W m^{-2} for early 1990s conditions (see Figure 4-5). This estimate had a large uncertainty and excluded the effects of cirrus cloud formation, which was deemed too uncertain to quantify. Although this represents only about 3.5% of the total anthropogenic forcing, the radiative forcing from aircraft has been predicted to increase by up to a factor of 11 (by 2050) compared with a predicted increase of roughly a factor of two in the total anthropogenic forcing (IPCC, 1999)[6]. At present, it is impossible to detect the effect of aircraft emissions alone in climatic observations and it may take several decades of sustained increases in aircraft emissions before this is possible. The largest areas of uncertainties were reported to be the interaction of NO_x with CH_4 reduction (see Section 4.3), contrail formation and the indirect effects of aviation on cirrus clouds (Section 4.4). This section details important advances in our understanding since the IPCC (1999)[6] report.

5.2.2 Carbon dioxide

5.2.2.1 The present emissions of CO_2 from aircraft (700 Tg yr^{-1}, EC, 2001[100]) are roughly 2% of that from the total anthropogenic emissions and contribute a smaller fraction of the total CO_2 radiative forcing, although this fraction is expected to increase over the next 100 years. These emissions will probably have only a small effect on surface temperature: for example, Sausen and Schumann (2000)[101], using a simple linear model, predict a rise in surface temperature of 0.05 K by 2100. These findings are similar to those quoted in IPCC (1999)[6].

5.2.3 Water vapour

5.2.3.1 Although stratospheric water vapour concentrations have been increasing (SPARC, 2000)[102] current subsonic aircraft emissions account for less than 5% of the water vapour increase (Danilin *et al*., 1998)[103]. This has been shown to have an insignificant radiative forcing (Schumann *et al.,* 2001)[104]. Furthermore, Marquart *et al*. (2001)[105] have shown that even if all aircraft burnt a hydrogen fuel their forcing from water vapour (not contrails) would remain insignificant. However,

if there were a large increase in supersonic transport, which injected large amounts of water vapour into the stratosphere, this could potentially have a large effect on climate (e.g. Manabe and Wetherald, 1967)[106].

5.2.4 Ozone

5.2.4.1 Several studies have found that the climate sensitivity may be different for O_3 changes than for other well-mixed greenhouse gas changes (Ponater *et al*., 1999[107], Hansen *et al*., 1997[96]; Forster and Shine, 1999[108]; Christiansen, 1999[109], Bintanja *et al*., 1996[110]; Stuber *et al*., 2001[111]). For this reason some authors are reluctant to quantify aviation effects in terms of their radiative forcing. However, there is still no clear mechanism, or indeed even a sign, for this difference. For example, Stuber *et al*. (2001)[111] find that the climate sensitivity for a upper tropospheric O_3 change is enhanced by about 60% through a feedback with stratospheric water vapour compared to that of carbon dioxide, whereas Hansen *et al*. (1997)[96] find a smaller enhancement due to cloud feedbacks and Christiansen (1999)[109] find a reduced climate sensitivity for tropospheric O_3 changes. We would therefore argue that until there is some uniformity between experiments, using different climate models, radiative forcing remains the most useful metric for assessing climate change.

5.2.4.2 An increase in supersonic transport would potentially deplete stratospheric O_3 and give a small negative radiative forcing (partially offsetting the effects of stratospheric water vapour, discussed above) and lead to a reduction in stratospheric temperatures (IPCC, 1999)[6]. For subsonic aircraft, Karlsdottir *et al*. (2000)[112] and Myhre *et al*. (2000)[113] have estimated the tropospheric ozone changes and their radiative effect between 1980–1996. Schumann *et al*. (2001)[104] scaled their findings with aircraft fuel consumption indices to estimate a 0.03–0.04 W m^{-2} radiative forcing in 2000. These numbers are only slightly higher than those estimated in IPCC (1999)[6]. Ponater *et al.* (1999)[107] estimated the equilibrium temperature response to tropospheric ozone changes until 2015 and found a global warming of 0.06–0.09 K which would account for up to 30% of the total effect of anthropogenic tropospheric ozone increases (IPCC, 2001)[64]. Finally, Sausen and Schumann (2000)[101] show that converting to a new combustion technology that reduces NO_X emissions, at the cost of increased fuel consumption, reduces the predicted global warming, as the O_3 radiative forcing is reduced by more than the CO_2 forcing is enhanced.

5.2.5 Methane

5.2.5.1 A reduction in the methane lifetime from increases in aircraft NO_X, acts as a negative radiative forcing. IPCC (1999)[6] estimated methane concentrations would be 2% higher without aircraft

emissions. This gives a negative forcing of approximately 0.01 W m^{-2} (IPCC, 2001)[64]. Recent experiments have indicated that aircraft induced methane loss may only be 0.6-1.2% (EC, 2001)[100], which suggests an even smaller forcing value for the methane loss.

5.2.6 Contrails and cirrus clouds

5.2.6.1 Contrails are usually thought of as thin cirrus clouds effecting both the shortwave and longwave radiation. Previous modelling studies have generally found that the extra trapping of longwave radiation usually dominates over the increased reflection of solar radiation, although this has not necessarily been confirmed by observations (Sassen ,1997)[114]. Their radiative effect is influenced by several factors including 1) the time of day they form, 2) the altitude at which they form, 3) the shape and size of the ice crystals 4) the surface they form over, including the effects of any underlying clouds. Previous studies of the contrail radiative forcing have therefore necessarily had to make many important assumptions. IPCC (1999)[6] used the value of global radiative forcing found by Minnis *et al*. (1999)[88] of 0.02 W m^{-2} as their best estimate for 1992. Since then, measurements of contrail optical depths over the USA and Europe suggest that the value of 0.3 used by Minnis *et al*. (1999)[88], although representative of the USA (Minnis *et al*., 2000)[115] may be too high over Europe, where observations showed optical depths averaging 0.1 (Meyer *et al*., 2001)[116].

5.2.6.2 Ponater *et al*. (2001)[93] incorporated a contrail parameterization into a climate model and found a similar difference in optical depth between the two continents, with even smaller values of optical depth over Europe (averaging 0.06). Partly as a result of this and partly as a result of contrails forming at different altitudes, Ponater *et al*. (2001)[93] estimated a smaller forcing (0.004 W m^{-2}) compared with the assessment of Minnis *et al*. (1999)[88] of 0.02 W m^{-2}, adopted by IPCC (1999)[6], this would be reduced still further if the contrail coverage data used in the climate models were updated using the data of Meyer *et al*. (2001)[116]. Myhre and Stordal (2001)[117] found a value of 0.01 W m^{-2} and showed, by hypothetically moving aircraft flights closer to sunrise and sunset, that a zero radiative forcing is obtainable.

5.2.6.3 Gierens *et al*. (1999)[87] and Sausen *et al*. (2001)[118] have predicted changes in contrail coverage until 2050, with increases in air traffic. Gierens *et al*. (1999)[87] predicted that global contrail coverage could increase to 0.75% by 2050 – a roughly 7-fold increase from the present. Sausen *et al*. (2001)[118] found smaller increases in contrails as they included the effects of global warming and found that less contrails form in a future (warmed) climate. They estimate a contrail coverage of 0.3% in 2050, which would very roughly imply a 2050 radiative forcing value from contrails of about 0.3 W m^{-2}, approximately 10% of the expected total anthropogenic CO_2 forcing at that

time. These results will, however, be model dependent and further evaluations are required using other models.

5.2.6.4 The effects of aircraft aerosol emissions and contrails on cirrus cloud formation is still unknown. Although aerosol emissions from aircraft are expected to have a negligible direct radiative forcing, their indirect effect could be significant by altering the chemistry of the atmosphere (particularly in the stratosphere – see Section 4.5) and altering cirrus clouds. A study by Rind *et al*. (1996)[119] arbitrarily increased cirrus cloud by 1% in their model and found a very large effect on surface temperature – a warming of 0.4 K. However, several important assumptions were made in this study and they found a very large climate sensitivity to cirrus clouds, which was 4 times larger than their greenhouse gas sensitivity. These findings would need to be verified by other models before any firm conclusions can be drawn.

6 FUTURE DEVELOPMENTS: TECHNOLOGY AND ATMOSPHERIC IMPACTS

6.1 Recent technological developments

6.1.1 That the IPCC report '*Aviation and the Global Atmosphere*' was a landmark, there can be no doubt. Since – and during – its writing and publication, there have been a number of significant events both in terms of airframe development and scientific research programmes. NASA has ceased support of the HSCT research efforts as Boeing withdrew its intention to develop a large SST. At the same time, NASA dramatically reduced its funding of research into subsonic effects in its SASS (Subsonic Assessment) research programme. In Europe, however, there has been a strong research effort put into place by the European Commission both in the environment and technology areas, particularly into the areas of emissions, particle and contrail effects, and potential tradeoffs in effects[4]. Other recent events in technology development include the intention of Airbus Industries to develop and build the A380, a competitor product to the Boeing 747, and Boeing's announcement of the proposed development of the 'Sonic Cruiser'. The impacts of such developments have yet to be assessed.

6.1.2 The A380 is a high-capacity subsonic aircraft and will carry around 600 passengers and is not anticipated to fly at significantly different altitudes to other similar large subsonic aircraft. The Boeing 'Sonic Cruiser', however, is being designed to fly at 45,000 – 50,000 feet (approximately 14 – 15 km) at Mach 0.95 – 0.98 (although Boeing have hinted at supersonic capability) and will thus spend a significant fraction of its time in the lower stratosphere, especially at more northerly latitudes (see Figure 4-2). Whilst O_3 depletion is unlikely to be a significant issue, because of the relatively low cruise altitude compared with previously assumed hypothetical SST cruise altitudes, it may be that the regime of the atmosphere is still conducive to significant O_3 production. For the same reasons of assumed cruise altitude, the water vapour introduced into the stratosphere may also have a radiative forcing effect somewhere between the IPCC assessments of subsonic and hypothetical supersonic fleets. Contrails, could be formed at equatorial latitudes but are less likely at northerly latitudes (when the aircraft is in the stratosphere). These effects are speculative, based upon experiences of previous assessments, and a full and careful assessment of various effects is required. Critical, of course, is the assumed fleet size, although it has been speculated that market uptake could be in the 1000s.

[4] see http://www.ozone-sec.ch.cam.ac.uk/clusters/Corsaire_Website/corsaire_index.htm

6.1.3 There are technology opportunities that can be pursued to effect an overall efficiency improvement in aircraft engines. These can be grouped into (a) improvements to current simple cycle bypass designs or (b) new, more complex engine cycles. It is clear that there will be no alternative to gas turbines for the foreseeable future.

6.1.3.1 Evolutionary engineering changes to the combustor have minimized increases in NO_x levels of more fuel-efficient engines and, in some cases, have led to reductions of 20% or more of the CAEP/2 standards. More significant reductions approaching 50% of CAEP/2 standards are under development and appear attainable within the next decade. Such reductions are being sought through, for example, the optimization of single-stage combustor technology, further improvements in fuel injection, enhanced fuel-air mixing, reduction in combustor liner coolant flow, with more air being made available for combustion, and decreases in hot-gas residence time.

6.1.4 Further reductions in NO_x to the ultra-low levels of 50 to 70% of the CAEP/2 standard may well require the use of the 'staged combustion concept'. Such an approach represents a revolutionary change in combustor design. Concepts of this type permit local temperature and residence time in the combustor to be controlled and optimized for each engine operating condition to minimize the amount of NO_x and other pollutants produced under all engine operating conditions. Large reductions of up to 90% of the CAEP/2 standard have been demonstrated in supersonic engine cycles. However, these do not readily translate to subsonic engines because of the higher combustor operating pressures that are likely with future high pressure ratio subsonic engines.

6.1.5 Advanced subsonic combustor approaches that show promise for low NOx, are multiple burning zones (as described above), variable geometry to control local fuel air ratios, and catalytic coatings on hot section parts to help initiate combustion and/or extend flammability limits of the primary combustion zone at low or intermediate engine power.

6.1.6 Recently, a study of the climate impacts of hypothetical aircraft design has been undertaken (GBD T-S, 2001; Greene, 2002)[120, 121]. In this study, the novel metric ‘greenhouse effect’ was devised and used to rank aircraft design. Moreover, a relationship between globally averaged radiative forcing (and summed from all effects) and engine bypass ratio was derived. Underlying the ‘greenhouse metric’ is the usage of GWPs for NO_x and water vapour for one particular latitude band and summer conditions, ignoring the effects of contrails. The use of GWPs for NO_x is inappropriate (IPCC, 1995)[62]. A relationship between engine bypass ratio and globally averaged total radiative forcing from all aircraft effects may be derived, but is erroneous as bypass ratio does not determine radiative forcing owing to NO_x nor resultant O_3. Nor does it determine contrail radiative forcing, as temperature and ice-supersaturation are the principal determinants of con-

trail formation, bypass ratio only having a second-order effect, through its influence on exhaust temperature. A fuller discussion of the determination of GWPs and radiative forcing in relation to aircraft effects in determining aircraft design and operation parameters is given in Box 1.

6.1.7 A radical longer-term proposition is the development of a fleet of liquid hydrogen (LH_2)-fuelled aircraft. Experimental aircraft have been built and a major European Commission Research Programme 'CRYOPLANE' is examining the technological feasibility and potential environmental impacts. If engines were to run on LH_2, they would emit no CO_2 or particles and a smaller amount of NO_x than conventional kerosene engines. However, despite the fact that no particles would be emitted, theoretical studies show that contrails would still form on background particles (Schumann 1996[84]; Kärcher *et al*., 1998[122]). A first study of RF of a hypothetical fleet of cryoplanes from has been made by Marquart *et al*. (2001)[105] who analysed two scenarios for 2015: the first, a conventional kerosene fleet which stayed constant in size; the second in which the fleet was instantaneously changed from kerosene to LH_2 powered in 2015 and then stayed constant. The instantaneous radiative forcing in 2015 is larger for the LH_2 powered fleet because of the differing optical properties of the contrails formed, however, by 2100, the LH_2 fleet has a smaller radiative forcing than the conventional fleet, because of the long-lasting effects of CO_2 from kerosene combustion. The two scenarios represent an unrealistic situation but the study is a parametric one. The environmental benefit would depend on the scenario adopted and, obviously, the outcome has very large uncertainties.

6.2 Policy responses, outstanding issues and options for mitigation

6.2.1 Proposals for a policy response to the IPCC report are currently effected through ICAO's Committee on Aviation Environment Protection (CAEP) work programmes because of aviation-specific issues. Normally, CO_2 emissions would come under the aegis of the UNFCCC. Currently, only domestic aviation emissions of CO_2 are accounted for in greenhouse gas emission inventories and therefore in the Kyoto Protocol. However, the Kyoto Protocol makes allowance for inclusion of international aviation and the UNFCCC, through its Subsidiary Body on Scientific and Technological Advice (SBSTA), has requested that ICAO's CAEP look at methods by which international aviation may be brought under the Kyoto Protocol. One favoured route is through CO_2 emissions trading (Gander and Helme, 1999)[123]. However, this ignores the fact that aviation has effects other than CO_2 on climate (see Figure 4-5) and that purchases of CO_2 permits by the aviation industry may increase total radiative forcing, not decrease it (Lee and Sausen, 2000)[124]. It has been shown in Section 5.3 that even ignoring contrail effects (which are highly uncertain), aircraft radiative forcing is twice that from its CO_2 emissions alone, and including contrail effects it is a factor of 3: both these multipliers ignore potential effects on cloudiness.

6.2.2 In parallel to the issue of emissions trading is that of emissions allocations. Since aviation is by its nature, international, the allocations of emissions is not straightforward although a number of allocations methodologies have been suggested by UNFCCC (1996)[(125)]. Before emissions of CO_2 can be traded, there must be some sort of allocation. Presently, these allocations are not known although initial work has started on this (Lee, 2002)[(126)], which shows that approximately 40 per cent of global civil aircraft emissions in 1992 were domestic and 60 per cent, international. Attribution by country by two of the commonly accepted allocation methodologies is also reported in this work.

6.2.3 Contrails and cirrus cloudiness remain an important issue. More research is currently being committed to understanding the basic physics of contrail formation through measurement programmes such as the EC Project INCA[5] and the German project 'PAZI'[6]. The formation of particles in the plume and the engine itself are only incompletely understood and the EC Project PARTEMIS[7] is specifically dealing with this issue. As elaborated in Section 5, significant uncertainties remain over contrail radiative forcing: although one of the more recent assessments of radiative forcing from line-shaped contrails indicates that the radiative forcing may be much smaller than calculated for IPCC (1999)[(6)].

6.2.4 Returning to one of the issues that initiated much of the research into the effects of subsonic aviation, NO_x emissions and O_3 production, this is still an issue with much uncertainty. The fallacy of O_3 positive radiative forcing 'cancellation' by negative CH_4 forcing from aircraft NO_x emissions has already been referred to. Radiative forcing by O_3 tends to be strongest in the Northern Hemisphere whilst negative forcing (i.e. a reduction in overall forcing) from CH_4 is spread across all latitudes. The real climate impact of opposing homogeneous and inhomogeneous forcings is not known. Remembering that radiative forcing is a proxy for climate change, it is necessary to understand the limits of its applicability. The IPCC (1999)[(6)] report broached the underlying issue, that of the adequacy of radiative forcing as a metric for aircraft climate impacts. There are two issues relevant to this discussion on O_3 radiative forcing: firstly, the temperature response to inhomogeneous forcings and; secondly, the temperature response to O_3 forcings at different altitudes.

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[5] see http://www.pa.op.dlr.de/inca/

[6] see http://www.pa.op.dlr.de/pazi/ - for more details of aviation-related EU and National research projects see http://www.ozone-sec.ch.cam.ac.uk/clusters/Corsaire_Website/corsaire_index.htm

[7] see http://www.cordis.lu/fp5/projects.htm

6.2.5 There is much work yet to be done before we can have higher confidence in assessments of the impacts of aviation on climate and establish methods by which these effects might be ameliorated. Tradeoffs between the different effects are the theme of a major European Commission research effort. In this project (TRADEOFF[8]), climate impacts are being examined together with those resulting from simple changes in operational methods. For example, it has already been shown by Sausen *et al*. (1998)[86] that flying 1 km lower or higher affects contrails in different ways, increasing contrail coverage for a 1 km downwards shift in parts of Eurasia and the NAFC but decreasing it in the tropics and North America. However, the effects on fuel efficiency and NO_x emissions were not considered. It has been calculated that a 2 km shift downwards may increase CO_2 and NO_x emissions by approximately 4.5 per cent (Lee *et al*., 2002b)[127]. This increase in CO_2 and NO_x, increases further by approximately 10% for a 3 km shift down and 20% for a 5 km shift downwards. A downward shift in cruise altitudes may decrease O_3 production, and thus its radiative forcing (Grewe *et al*., 2002)[128]; however, contrails at lower altitudes may have stronger radiative properties because of their higher water content (Meerkötter *et al*., 1999)[129].

6.2.6 A recent operational development is the opening up of polar routes. Until recently, very little traffic crossed the north polar region, a situation which is rapidly changing. This region is potentially rather sensitive, even to current subsonic aircraft, as the tropopause is at its lowest during polar night. Temperatures can fall to very low values and a so-called polar vortex can be established in which any deposited pollutants may be removed only very slowly. A build-up of particles, NO_x and H_2O emissions from aircraft may have deleterious effects on stratospheric ozone as PSC formation could possibly be enhanced. The increased sensitivity of climate effects to high latitude forcings (Hansen *et al.,* 1997[96]; Forster *et al.,* 2000[97]) will also play an important role in determining the atmospheric impact of polar routes. Such effects are however speculative, with preliminary studies being performed within the TRADEOFF project.

6.2.7 Thus, it can be seen that operational changes have complex environmental responses, which are not yet fully understood, let alone verified. It is premature to even begin thinking through the economic and technological consequences of changing operational practices for environmental purposes until studies are scientifically defensible and robust (Lee *et al*., 2000)[92].

[8] see http://www.ozone-sec.ch.cam.ac.uk/clusters/Corsaire_Website/corsaire_euproj.htm

7 CONCLUSIONS

- The growth of the aviation industry and air travel/transport is likely to continue in the future and environmental concerns will increase, not decrease, as technological improvements in emissions will be outstripped by growth of the global fleet.

- There are significant concerns that future growth in aviation will adversely affect climate and local air quality in the vicinity of airports. The impacts of aircraft on climate have been studied intensively but many scientific uncertainties and open questions remain. Assessments of aircraft emissions on local air quality are poorly developed and the available modelling tools are, in general, inadequate.

- Whilst air quality concerns from aircraft emissions predate those over effects on global climate, the issue is re-emerging as air quality standards become more stringent and airport growth becomes an issue. It is more common to expand existing airports than to build new ones in order to cope with increased demand, a situation that tends to exacerbate air quality problems for a given regional capacity. It is possible that air quality may become a constraint to increased capacity of some large hub airports.

- The current metric for comparing effects of different emissions and sources on global climate is radiative forcing, expressed in Watts per square metre (W m^{-2}). At present, the impact of aircraft represents 0.05 W m^{-2}, or 3.5% of total anthropogenic radiative forcing, an estimate which excludes the possible forcing arising from enhanced cirrus cloud formation from aircraft emissions. By 2050, according to a mid-range scenario, the radiative forcing from aircraft will be 0.19 W m^{-2}, or 5% of the total radiative forcing from anthropogenic activities.

- Aircraft have approximately three times the radiative forcing impact that would be expected from their CO_2 emissions alone. This factor would be increased if the effects on cirrus are verified. Depending upon the emission scenario employed, by 2050 aircraft could account for over 10% of the CO_2 radiative forcing and up to a third of the tropospheric O_3 radiative forcing. This unique property of aviation emissions of having a larger radiative forcing than implied by their CO_2 emissions alone is not currently accounted for in emissions trading scheme proposals being developed by the International Civil Aviation Organization. By considering only CO_2 emissions from aviation, emissions trading could, in theory, increase total anthropogenic radiative forcing, rather than decrease it.

- Significant uncertainties remain in quantifying aircraft effects on radiative forcing. The effects of line-shaped contrails remain very uncertain although smaller values of radiative forcing have recently been calculated. Nonetheless, there does not appear to be any convergence of results. No reliable estimate of the potential radiative forcing effect from aircraft-induced cirrus cloud has yet been made.

- The effects of aircraft NO_x emissions on tropospheric O_3 radiative forcing remain a significant issue, despite its concomitant effect of reducing concentrations of CH_4, another radiatively active gas. In fact, there is growing evidence that the northern hemisphere bias of aircraft-induced tropospheric O_3 forcing has a stronger climate effect than equivalent homogeneous forcing from CO_2.

- The study of more 'environmentally friendly' flight through changed cruise altitudes, radical technological changes and changed routings is in its infancy. These studies require complex quantitative modelling and assessment tools and the results, at present, are likely to have large uncertainties. Nonetheless, such studies are required with parallel effort committed to refining such tools, in order to ultimately aid future aircraft design and produce more definitive assessments of aircraft impacts on climate. Neither the science nor the modelling tools are well enough developed to quantify environmental effects into aircraft/engine design parameters, other than the effects of CO_2.

- A number of proposed and actual new developments in terms of technology and operational practice require environmental assessment. A recommendation of this paper would therefore be to conduct an audit of the current and planned UK and European aerospace research programmes and objectives, in order to assess the extent to which they address the environmental concerns raised in this paper.

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8 REFERENCES

1. ICAO (1981) International standards and recommended practices, environmental protection. Annex 16 to the Convention on International Civil Aviation, Volume II, aircraft engine emissions, 1st Edition, International Civil Aviation Organization, Montreal.
2. ICAO (1995) ICAO Engine Exhaust Emissions Databank, 1st Edition—1995, ICAO Doc. 9646-AN/943, International Civil Aviation Organization, Montreal.
3. Johnston, H. S. (1971) Reduction of stratospheric ozone by nitrogen dioxide catalysts from supersonic transport exhaust. *Science* **173**, 517–522.
4. Crutzen, P. J. (1972) SSTs: a threat to the earth's ozone shield. A*mbio* **1**, 41–51.
5. Schumann, U. (1990) Air Traffic and the Environment, Lecture Notes in Engineering, 60 U. Schumann (ed.), Springer-Verlag, Berlin.
6. IPCC (1999) *Aviation and the Global Atmosphere*. A Special Report of IPCC Working Groups I and III in collaboration with the Scientific Assessment panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, J. E. Penner, D. H. Lister, D. J. Griggs, D. J. Dokken and M. McFarland (eds). Intergovernmental Panel on Climate Change, Cambridge University Press, UK.
7. Schumann, U. (1994) On the effect of emissions from aircraft engines on the state of the atmosphere. *Annales Geophysicae* **12**, 365–384.
8. Wahner, A., Geller, M. A., Arnold, F., Brune, W. H., Cariolle, D. A., Douglass, A. R., Johnson, C., Lister, D. H., Pyle, J. A., Ramaroson, R., Rind, D., Rohrer, F., Schumann, U. and Thompson, A. M. (1995) Subsonic and supersonic aircraft emissions. In 'Scientific Assessment of Ozone Depletion: 1994' World Meteorological Organization Global Ozone Research and Monitoring project—Report No. 37, Geneva.
9. Friedl, R. R., Baughcum, S. L., Anderson, B., Hallett, J., Liou, K.-N., Rasch, P., Rind, D., Sassen, K., Singh, H., Williams, L. and Wuebbles, D. (1997) Atmospheric effects of subsonic aircraft: interim assessment of the advanced subsonic assessment program. NASA Reference Publication 1400, Washington D. C., USA.
10. Brasseur, G. P., Cox, R. A., Hauglustaine, D., Isaksen, I., Lelieveld, J., Lister, D. H., Sausen, R., Schumann, U., Wahner, A. and Wiesen, P. (1998) European scientific assessment of the atmospheric effects of aircraft emissions. *Atmospheric Environment* **32**, 2329–2418.
11. Döpelheuer, A. (2001) Quantities, characteristics and reduction potentials of aircraft engine emissions, SAE Paper No. 2001-01-3008, Proceedings of the 2001 Aerospace Congress, September 10–14, 2001.
12. Petzold, A., Döpelheuer, A., Brock, C. A. and Schröder, F. P. (1999) In situ observations and model calculations of black carbon emission by aircraft at cruise altitude. *Journal of Geophysical Research* **104**, 22171–22181.
13. Miake-Lye, R. C., Martinez-Sanchez, M., Brown, R.C. and Kolb, C. E. (1993) Plume and wake dynamics, mixing and chemistry behind an HSCT aircraft. *Journal of Aircraft* **30**, 467–479.

14. Lukachko, S. P., Waitz, I. A., Miake-Lye, R. C., Brown, R. C. and Anderson, M. R. (1998) Production of sulfate aerosol precursors in the turbine and exhaust nozzle of an aircraft engine. *Journal of Geophysical Research* **103**, 16159–16174.

15. Curtuis, J., Sierau, B., Arnold, F., Baumann, R., Busen, R., Schulte, P. and Schumann, U. (1998) First direct sulfuric acid detection in the exhaust plume of a jet aircraft in flight. *Geophysical Research Letters* **25**, 923–926.

16. Hanisco, T. F., Wennberg, P. O., Cohen, R. C., Anderson, J. G., Fahey, D. W., Keim, E. R., Gao, R. S., Wamsley, R. C., Donnelly, S. G., DelNegro, L. A., Salawitch, R. J., Kelly, K. K. and Proffitt, M. H. (1997) The role of HO_x in super- and subsonic aircraft exhaust plumes. *Geophysical Reearch Letters* **24**, 65–68.

17. Tremmel, H. G., Schlager, H., Konopka, P., Schulte, P., Arnold, F., Klemm, M. and Droste-Franke, B. (1998) Observations and model calculations of jet aircraft exhaust products at cruise altitude and inferred OH emissions. *Journal of Geophysical Research* **103**, 10803–10816.

18. Bockle, S., Einecke, S., Hildenbrand, F., Orlemann, C., Schulz, C., Wolfrum, J. and Sick, V. (1999) Laser-spectroscopic investigation of OH-radical concentrations in the exhaust plane of jet engines. *Geophysical Research Letters* **26**, 1849–1852.

19. Arnold, F., Scheid, J., Stilp, T., Schlager, H. and Reinhardt, M. E. (1992) Measurement of jet aircraft emissions at cruise altitude. I. The odd nitrogen gases. *Geophysical Research Letters* **19**, 2421–2424.

20. Frenzel, A. and Arnold, F. (1994) Sulphur acid cluster ion formation by jet engines: implications fo sulfuric acid formation and nucleation. In '*Impact of Emissions from Aircraft and Spacecaft on the Atmosphere*' Proceedings of an International Scientific Colloquium, Köln (Cologne), Germany, April 18–20, 1994, U. Schumann and D. Wurzel (eds), DLR Mitteilung 94-06, Köln.

21. Arnold, F., Curtuis, J., Sierau, B., Bürger, V., Busen, R. and Schumann (1999) Detection of massive negative chemiions in the exhaust plume of a jet aircraft in flight. *Geophysical Research Letters* **26**, 1577–1580.

22. Wohlfrom, K. H., Eichkorn, S., Arnold, F. and Schulte, P. (2000) Massive positive and negative ions in the wake of a jet aircraft: Detection by a novel aircraft-based large ion mass spectrometer (LIOMAS). *Geophysical Research Letters* **27**, 3853–3856.

23. Yu, F. Q. and Turco, R. P. (1997) The role of ions in the formation and evolution of particles in aircraft plumes. *Geophysical Research Letters* **24**, 1927–1930.

24. Henderson, S. C., Wickrama, U. K., Baughcum, S. L., Begin, J. L., Franco, F., Greene, D. L., Lee, D. S., Mclaren, M. L., Mortlock, A. K., Newton, P. J., Schmitt, A., Sutkus, D. J., Vedantham, A., and Wuebbles, D. J. (1999) Aircraft emissions: current inventories and future scenarios. Chapter 9 of '*Aviation and the Global Atmosphere*' J. E. Penner, D. H. Lister, D. J. Griggs, D. J. Dokken and M. McFarland (eds). A Special Report of IPCC Working Groups I and III in collaboration with the Scientific Assessment panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, Intergovernmental Panel on Climate Change, Cambridge University Press.

25. Gardner, R. M., Adams, J. K., Cook, T., Larson, L. G., Falk, R. S., Fleuti, 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., Have, H. ten and 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.

26. Schmitt, A. and Brunner, B. (1997) Emissions from aviation and their development over time, In: Final Report on the BMBF Verbundprogramm, '*Schadstoffe in der Luftfahrt'* U. Schumann, A. Chlond, A. Ebel, B. Kärcher, H. Pak, H. Schlager, A. Schmitt and P. Wendling (eds), DLR Mitteilung 97-04.

27. Baughcum, S. L., Tritz, T. G., Henderson, S. C. and Pickett, D. C. (1996) Scheduled Civil Aircraft Emissions Inventories for 1992: Data base Development and Analysis. NASA Contractor report 4700, NASA Langley Research Center, US.

28. Baughcum, S. L., Henderson, S. C. and Sutkus, D. J. (1998) Scheduled Civil Aircraft Emission Inventories Projected for 2015: Database Development and Analysis, NASA/CR-1998-207638, NASA Langley Research Center, US.

29. 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.

30. Newton, P. J. and Falk, R. S. (1997) DTI forecast of fuel consumption and emissions from civil aircraft in 2050 based on ANCAT/EC2 1992 data, DTI Report No. DTI/ADI3c/199701/1.0.

32. Lee, D. S., Brunner, B., Döpelheuer, A., Falk, R. S., Gardner, R. M., Lecht, M., Leech, M., Lister, D. H. and Newton, P. J. (2002a) Aviation emissions: present-day and future. *Meteorologische Zeitschrift* (accepted for publication).

33. IPCC (2000) Emission Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK.

34. Leggett, J., Pepper, W. J. and Swart, R. J. (1992) Emissions scenarios for IPCC: an update. In *Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment*. J. T. Houghton, B.A. Callander and S.K. Varney (eds), Cambridge University Press, Cambridge.

35. IPCC (1996) Climate Change 1995, the Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. J. T. Houghton, L. G. Meira Filho, Callander, E. Haites, N. Harris, A. Kattenberg and K. Maskell. (eds), Cambridge University Press, UK.

36. Anderson, B. E., Cofer, W. R., Crawford, J., Gregory, G. L., Vay, S. A., Brunke, K. E., Kondo, Y., Koike, M., Chlager, H., Baughcum, S. L., Jensen, E., Zhao, Y. and Kita, K. (1999) An assessment of aircraft as a source of particles to the upper troposphere. *Geophysical Research Letters* **26**, 3069–3072.

37. Lee, D. S., Köhler, I., Grobler, E., Rohrer, F., Sausen, R., Gallardo-Klenner, L, Olivier, J. J. G., Dentener, F. D. and Bouwman, A. F. (1997) Estimations of global NO_x emissions and their uncertainties. *Atmospheric Environment* **31**, 1735–1749.

38. Holland, E. A., Dentener F. J., Braswell B. H. and Sulzman J. M. (1999) Contemporary and pre-industrial reactive nitrogen budgets. *Biogochemistry* **46**, 7–43.

39. Prather, M. and Ehalt, D. (2001) Atmospheric chemistry and greenhouse gases. Chapter 4 in '*Climate Change 2001: The Scientific Basis*' J. T. Houghton et al. (eds), contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, UK.

40. Prentice, I. C. (2001) The carbon cycle and atmospheric carbon dioxide. Chapter 3 in '*Climate Change 2001: The Scientific Basis*' J. T. Houghton et al. (eds), contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, UK.

41. Bergamaschi, P., Hein, R., Heimann, M. and Crutzen, P. J. (2000) Inverse modeling of the global CO cycle 1. inversion of CO mixing ratios. *Journal of Geophysical Research* **105**, 1909–1927.

42. Oxford Economic Forecast (1999) The Contribution of Aviation to the UK Economy.

43. Thomas, C. S. and Raper, D. W. (2000) The role of aero engineering in the sustainable development of the aviation industry. *Aeronautical Journal* July 2000, 331–333.

44. Tunstall-Pedoe, N., Raper, D. W. and Holden, J. (Eds) (1996) *Airports and the Environment—liabilities and social responsibilities*. Proceedings of International Conference, Manchester Airport July 1995, Thomas Telford, London.

45. BAA (2001). Proposed development at Stanstead Airport: Environmental Statement volume 10.

46. ICAO (1993) International standards and recommended practices, environmental protection. Annex 16 to the Convention on International Civil Aviation, Volume II, aircraft engine emissions, 2nd Edition, International Civil Aviation Organization, Montreal.

47. Bjørnstom, H., Westerberg, J., Nas, P. and Palsson, A. (2001) Research into operational procedures. Workpackage 2 report of AEROCERT, Contract No AI-97-SC.242.

48. Webb, S. (1995) Technical data to support FAA's advisory circular on reducing emissions from commercial aviation. Energy and Environmental analysis INC. Virginia USA. (http://www.aee.faa.gov/emissions/faa-ac.pdf).

49. Lindley, S. J., Conlan, D. E., Raper, D. W. and Watson, A. F. R. (1999) Estimation of spatially resolved road and transport emissions for air quality management applications in the north west region of England. *Science of the Total Environment* **235**, 119–132.

50. Owen, B., Edmunds, H. A., Carruthers, D. J. and Raper, D. W. (1999) Use of a new generation urban scale dispersion model to estimate the concentration of oxides of nitrogen, nitrogen dioxide and sulphur dioxide in a large urban area. *Science of the Total Environment* **235**, 277–291.

51. Wayson, R. and Fleming, G. (2000) Consideration of air quality impacts by airplane operations at or above 3000 feet AGL. US Department of Transport, Federal Aviation Administration. FAA-AEE-00-01 DTS-34, Washington USA.

52. Pasquill, F. and Smith, F. B. (1983) *Atmospheric Diffusion*. Third edition, Ellis Horwood, Chichester.

53. Jung, H. J. (2000) Entwicklung und Erpropung einer Method zur Bewertung der Schadstoffimmisionen in der Umgebung von Flugplätzen. Band II Ermittlung der Imissiononen. Umweltbundesamt Forschungsbericht 294 436 89, Berlin.

54. Staehelin, J., Harris, N. R. P., Appenzeller C. and Eberhard J. (2001) Ozone trends: a review. *Review of Geophysics* **39**, 231–290.

55. WMO (1999) Scientific Assessment of Ozone Depletion: 1998. World Meteorological Organization Global Ozone Research and Monitoring Project—Report No. 44, Geneva.

56. SORG (1996) Stratospheric ozone 1996. United Kingdom Stratospheric Ozone Review Group, Department of the Environment, Transport and the Regions, London.

57. SORG (1999) Stratospheric ozone 1999. United Kingdom Stratospheric Ozone Review Group, Department of the Environment, Transport and the Regions, London.

58. Dobson, G. M. B. (1930) The ozone in the earth's upper atmosphere. *Beiträge zur Physik der freien Atmosphäre* **16**, 76–85.

59. Brewer, A. (1949) Evidence for a world circulation provided by the measurements of helium and water vapor distributions in the stratosphere. *Quarterly Journal of the Royal Meteorological Society* **75.**

60. Labitzke, K. G. and van Loon, H. (1999) *The Stratosphere. Phenomena, History and Relevance*. Springer Verlag, Berlin.

61. Seinfeld, J. H. and Pandis, S. N. (1998) *Atmospheric chemistry and physics—from air pollution to climate change*. John Wiley and Sons, New York.

62. IPCC (1995) Climate Change 1994. Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios. Reports of Working Groups I and III of the Intergovernmental Panel on Climate Change, forming part of the IPCC Special Report to the first session of the Conference of the Parties to the UN Framework Convention on Climate Change. J. T. Houghton, L. G. Meira Filho, J. Bruce, Hoesung Lee, B. A. Callander, E. Haites, N. Harris and K. Maskell. (eds), Cambridge University Press, UK.

63. Harries, J. E., Brindley, H. E., Sagoo, P. J. and Bantges, R. J. (2001) Increases in greenhouse forcing inferred from the outgoing longwave radiation spectra of the Earth in 1970 and 1997. *Nature* **410**, 355–357.

64. IPCC (2001) Climate Change 2001, the Scientific Basis. Summary for policymakers and technical Summary of the Working Group I Report. Cambridge University Press, UK.

65. McIlveen, R. (1992) *Fundamentals of Weather and Climate* . Chapman and Hall, London, UK.

66. McGuffie, K. and Hendersen-Sellers, A. (1997) *A Climate Modelling Primer*. John Wiley & Sons, Chichester, UK.

67. IPCC (1997) An introduction to simple claimte models used in the IPCC Second Assessment Report. IPCC Technical Paper II, J.T. Houghton, L. Gylvan Meira Filho, D.J. Griggs and K. Maskell (eds), Intergovernmental Panel on Climate Change, Switzerland.

68. IPCC (1990) Climate Change, the IPCC Scientific Assessment., J.T. Houghton, G.J. Jenkins and J.J. Ephraums (eds), Cambridge University Press, UK.

69. Shine, K. P. and Forster, P. M. de F. (1999) The effect of human activity on radiative forcing of climate change: a review of recent developments. *Global and Planetary Change* **20**, 205–225.

70. Forster, P. M. D. and Shine, K. P. (1997) Radiative forcing and temperature trends from stratospheric ozone changes. *Journal of Geophysical Research* **102**, 10841–10855.

71. Hein, R., Dameris, M., Schnadt, C., Land, C., Grewe, V., Köhler, I., Ponater, M., Sausen, R., Steil, B., Landgraf, J. and Brühl, C. (2001) Results of an interactively coupled atmospheric chemistry–general circulation model: comparison with observations. *Annales Geophysicae* **19**, 435–457.

72. Lee, D. S. and Raper, D. W. (2002) Global atmospheric impacts. In '*Towards Sustainable Aviation: Trends and Issues*' P. Upham, C. Thomas, D. W.Raper and J. Maughan (eds). EarthScan Publications Ltd, London (in press).

73. Grooß, J.-U., Brühl, C. and Peter, T. (1998) Impact of aircraft emissions on tropospheric and stratospheric ozone. Part 1: chemistry and 2-D model results. *Atmospheric Environment* **32**, 3173–3184.

74. Jaeglé, L., Jacob, D. J., Brune, W. H., Faloona, I. C., Tan, D., Kondo, Y., Sachse, G. W., Anderson, B., Gregory, G. L., Vay, S., Singh, H. B., Blake, D. R. and Shetter, R. (1999) Ozone production in the upper troposphere and the influence of aircraft during SONEX: approach of NO_x-saturated conditions. *Geophysical Research Letters* **26**, 3081–3084.

75. Grewe, V., Dameris, M., Hein, R., Köhler, I. and Sausen, R. (1999) Impact of future subsonic aircraft NOx emissions on the atmospheric composition. *Geohpyiscal Research Letters* **26**, 47–50.

76. Fuglestvedt, J. S., Isaksen, I. and Wang, W.–C. (1996) Estimates of indirect global warming potentials for CH_4, CO and NO_x. *Climatic Change* **34**, 405–437.

77. Ewins, P. (2000) The truth about global warming. *The Aeronautical Journal* July, 311–320.

78. Appleman, H. S. (1966) Effect of supersonic aircraft on cirrus formation and climate. American Meteorological Society and American Institute of Aeronautics and Astronautics, Conference on Aerospace Meteorology, Los Angeles, California, March 28–31, 1966, AIAA Paper 66-369.

79. Chagnon, S. A. (1981) Midwestern cloud, sunshine and temperature trends since 1901: possible evidence of jet contrail effects. *Journal of Applied Meteorology* **20**, 496–508.

80. Schumann, U. and Wendling, P. (1990) Determination of contrails from satellite data and observational results. In '*Air traffic and the environment—background, tendencies, and potential global atmospheric effects*' U. Schumann (ed.), Springer-Verlag, Heidelberg, pp138–153.

81. Tremmel, H. G. and Schumann, U. (1999) Model simulations of fuel sulfur conversion efficiencies in an aircraft engine. Dependence on reaction rate constants and initial species mixing ratios. *Aerospace Science and Technology* **3**, 417–430.

82. Anderson, B. E., Cofer, W. R., Barrick, J. W., Bagwell, D. R., Hudgins, C. H. and Nowicki, G. D. (1998) Airborne observations of aircraft aerosol emissions. 1. Total and nonvolatile particle emission indices. *Geophysical Research Letters* **25**, 1689–1692.

83. Schröder, F. P., Kärcher, B., Petzold, A., Baumann, R., Busen, R., Hoell, C. and Schumann, U. (1998) Ultrafine aerosol particles in aircraft plumes: *in situ* observations. *Geophysical Research Letters* **25**, 2789–2792.

84. Schumann, U. (1996) On conditions for contrail formation from aircraft exhausts. *Meteorologische Zeitschrift* **5**, 4–23.

85. Kärcher, B. (1999) Aviation-produced aerosols and contrails. *Surveys in Geophysics* **20**, 113–167.

86. Sausen, R., Gierens, K., Ponater, M. and Schumann, U. (1998) A diagnostic study of the global distribution of contrails part I: Present day climate. *Theoretical and Applied Climatology* **61**, 127–141.

87. Gierens, K., Sausen, R. and Schumann, U. (1999) A diagnostic study of the global distribution of contrails part II: future air traffic scenarios. *Theoretical and Applied Climatology* **63**, 1–9.

88. Minnis, P., Schumann, U., Doelling, D. R., Gierens, K. R. and Fahey, D. W. (1999) Global distribution of contrail radiative forcing. *Geophysical Research Letters* **26**, 1853–1856.

89. Liou, K. N. (1986) Influence of cirrus clouds on weather and climate processes: a global perspective. *Monthly Weather Review* **114**, 1167–1199.

90. Lohmann, U. and Roeckner E. (1995) Influence of cirrus cloud radiative forcing on climate and climate sensitivity in a general circulation model. *Journal of Geophysical Research* **100**, 16305–16323.

91. Boucher, O. (1999) Air traffic may increase cirrus cloudiness. *Nature* **397**, 30–31.

92. Lee, D. S., Clare, P. E., Haywood, J., Kärcher, B., Lunnon, R. W., Pilling, I., Slingo, A. and Tilston, J. R. (2000) Identifying the uncertainties in radiative forcing of climate from aviation contrails and aviation-induced cirrus. DERA/AS/PTD/CR000103, DERA Pyestock.

93. Ponater, M., Marquart, S. and Sausen, R. (2001) Contrails in a comprehensive global climate model: parameterisation and radiative forcing results. DLR Institut für Physik der Atmosphäre Report No. 147, Oberpfaffenhofen and submitted to *Journal of Geophysical Research*

94. Hofmann, D. J. (1990) Increase in stratospheric background sulfuric acid aerosol mass in the past 10 years. *Science* **248**, 996–1000.

95. Rogers, H. L., Chipperfield, M. P., Bekki, S. and Pyle, J. A. (2000) The effects of future supersonic aircraft on stratospheric chemistry modeled with varying meteorology. *Journal of Geophysical Research* **105**, 29359–29367.

96. Hansen, J. E., Sato, M. and Ruedy, R. (1997) Radiative forcing and climate response. *Journal of Geophysical Research* **102**, 6831–6684.

97. Forster, P. M. de F., Blackburn, M., Glover, R. and Shine, K. P. (2000) An examination of climate sensitivity for idealised climate change experiments in an intermediate general circulation model. *Climate Dynamics* **2000**, 833–849.

98, Lindzen, R. S., Chou, M. D. and Hou, A. Y. (2001) Does the earth have an adaptive infrared iris? *Bulletin of the American Meteorological Society* **82**, 417–432.

99. Ramaswamy, V., Chanin, M. L., Angell, J., Barnett, J., Gaffen, D., Gelman, M., Keckhut, P., Koshelkov, Y., Labitzke, K., Lin, J. J. R., O'Neill, A., Nash, J., Randel, W., Rood, R., Shine, K., Shiotani, M., and Swinbank, R. (2001) Stratospheric temperature trends: Observations and model simulations. *Reviews of Geophysics* **39**, 71–122.

100. EC (2001), European research in the stratosphere 1996-2000: Advances in our understanding of the ozone layer during THESEO, EUR 19867.

101. Sausen, R. and Schumann, U. (2000) Estimates of the climate response to aircraft CO_2 and NO_x emissions scenarios. *Climatic Change* **44**, 27–58.

102. SPARC (2000) SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapour Verrieres Le Buisson Cedex, Stratospheric Processes and their Role in Climate, WCRP-113, WMO-TD No 1043, SPARC Report 2**:** 31.

103. Danilin, M. Y., Fahey, D. W., Schumann, U., Prather, M. J., Penner, J. E., Ko, M. K. W., Weisenstein, D. K, Jackman, C. H., Pitari, G., Köhler, I., Sausen, R., Weaver, C. J., Douglass, A. R., Connell, P.S., Kinnison, D. E., Dentener, F. J., Fleming, E. L., Berntsen, T. K., Isaksen, I. S. A., Haywood J. M., and Karcher, B. (1998) Aviation fuel tracer simulation: Model intercomparison and implications. *Geophysical Research Letters* **25**, 3947–3950.

104. Schumann, U., Ström, J., Arnold, F., Bernsten, T. K., Forster, P. M. de F., Gayet, J.-F. and Hauglustaine, D. (2001). Aviation impact on atmospheric composition and climate. Second European Assessment of Stratospheric Research.

105. Marquart, S., Sausen, R., Ponater, M. and Grewe, V. (2001) Estimate of the climate impact of cryoplanes. *Aerospace Science and Technology* **5**, 73–84.

106. Manabe, S. and Wetherald, R. T. (1967) Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *Journal of the Atmospheric Sciences* **24**, 241–259.

107. Ponater, M., Sausen, R., Feneberg, B. and Roeckner, E. (1999) Climate effect of ozone changes caused by present and future air traffic. *Climate Dynamics* **15**, 631–642.

108. Forster, P. M. de F., and Shine, K. P. (1999) Stratospheric water vapour changes as a possible contributor to observed stratospheric cooling. *Geophysical Research Letters* **26**, 3309–3312.

109. Christiansen, B. (1999) Radiative forcing and climate sensitivity: The ozone experience. *Quarterly Journal of the Royal Meteorological Society* **125**, 3011–3035.

110. Bintanja, R., Fortuin, J. P. F. and Kelder, H. (1996) Simulation of the meridionally and seasonally varying climate response caused by changes in ozone concentration. *Journal of Climate* **10**, 1288–1311.

111. Stuber, N., Sausen, R. and Ponater, M. (2001) Stratosphere adjusted radiative forcing calculations in a comprehensive climate model. *Theoretical and Applied Climatology* **68**, 125–135.

112. Karlsdottir, S., Isaksen, I. S. A., Myhre, G., and Berntsen, T. K. (2000) Trend analysis of O_3 and CO in the period 1980-1996: A three- dimensional model study. *Journal of Geophysical Research* **105**, 28907–28933.

113. Myhre, G., Karlsdottir, S., Isaksen, I. S. A. and Stordal, F. (2000) Radiative forcing due to changes in tropospheric ozone in the period 1980 to 1996. *Journal of Geophysical Research* **105**, 28935–28942.

114. Sassen, K. (1997) Contrail-cirrus and their potential for regional climate change. *Bulletin of the American Meteorological Society* **78**, 1885–1903.

115. Minnis, P., Palikonda, R. Ayers, J. K., Duda, D. P. and Costulis, P. K. (2000). Cirrus, contrails and radiative forcing over the USA: their relationship to air trafic and upper tropospheric conditions. Aviation, Aerosols, Contrails and Cirrus Clouds. U. S. a. G. T. Amanatidis. Seeheim, Germany, European Commission, Brussels**:** 193-196.

116. Meyer, R., Mannstein, H., Meerkötter, R., Schumann, U. and Wendling, P. (2001) Regional radiative forcing by line-shaped contrails derived from satellite data. *Journal of Geophysical Research* (submitted).

117. Myhre, G. and Stordal, F. (2001) On the tradeoff of the solar and thermal infrared radiative impact of contrails. *Geophysical Research Letters* **28**, 3119-3122.

118. Sausen, R., Mager, F., Gierens, K. and Ponater, M. (2001) A diagnostic study of of the global distribution of contrails. Part III: impact of climate change. *Theoretical and Applied Climatology* (submitted).

119**.** Rind, D., Lonergan, P. and Shah, K. (1996) Climatic effect of water vapour release into the upper troposphere. *Journal of Geophysical Research* **100**, 7381–7396

120. GBD-TS (2001) Air travel—Greener by Design, the Technology Challenge.

121. Green J. E. (2002) Greener by Design – the technology challenge. *The Aeronautical Journal* **106**, 57–113.

122. Kärcher, B., Busen, R., Petzold, A., Schröder, F. and Schumann, U. (1998) Physiochemistry of aircraft-generated liquid aerosols, soot, and ice particles. 2 Comparison with observations and sensitivity studies. *Journal of Geophysical Research* **103**, 17129–17147.

123. Gander, S. and Helme, N. (1999) Emissions trading is an effective, proven policy tool for solving air pollution problems. *ICAO Journal* **54**, 12–14, 28.

124. Lee, D. S. and Sausen, R. (2000) New Directions: Assessing the real impact of CO_2 emissions trading by the aviation industry. *Atmospheric Environment* **34**, 5337–5338.

125. UNFCCC (1996) Communications from Parties included in Annex I to the convention: guidelines, schedules, and process for consideration. Secretariat note FCCC/SBSTA 1996/9/Add. 1, United Nations Framework Convention on Climate Change, 8 July, 1996, Geneva, Switzerland.

126. Lee, D. S. (2002) Allocating international civil aviation emissions. In preparation for *Climatic Change*.

127. Lee, D. S., Sausen, R. and Norman, P. D. (2002b) The effect of changing cruise altitudes on emissions of NO_x and CO_2 for the global civil aircraft fleet. In preparation for *Aerospace Science and Technology.*

128. Grewe, V., Dameris, M., Fichter, C. and Lee, D. S. (2002) Impact of aircraft NO_x emissions. Part 2: effects of lowering the flight altitude. *Meteorologishe Zeitschrift* (in press).

129. Meerkötter, R., Schumann, U. , Dölling, D. R. , Minnis, P. and Nakajima, T. (1999) Radiative Forcing by Contrails. *Annales Geophysicae* **17**, 1080–1094.

130. Chapman, S. (1930) A theory of upper atmosphere ozone. *Memoirs of the Royal Meteorological Society* **3**, 103–125.

131. Singh, H. B., Kanakidou, M., Crutzen, P. J. and Jacob, D. J. (1995) High concentrations and photochemical fate of oxygenated hydrocarbons in the global troposphere. *Nature* **378**, 50–54.

132. Wennberg, P. O., Hanisco, T. F., Jaeglé, L., Jacob, D. J., Hinsta, E. J., Lanzendorf, E. J., Anderson, J. G., Gao, R. S., Keim, E. R., Donnelly, S. G., Del Negro, L. A., Fahey, D. W., McKeen, S. A., Salawitch, R. J., Webster, C. R., May, R. D., Herman, R. L., Proffitt, M. H., Margitan, J. J., Atlas, E. L., Schauffler, S. M., Flocke, F., McElroy, C. T. and Bui, T. P. (1998) Hydrogen radicals, nitrogen radicals and the production of ozone in the upper troposphere. *Science* **279**, 49–53.

9 GLOSSARY

Acronym/Unit	Description
APU	Auxiliary power units
BrO_x	Bromine oxides
CAEP	Committee on Aviation Environmental Protection
CH_4	Methane
CIs	Chemi-ions
ClO_x	Chlorine oxides
CO	Carbon monoxide
CO_2	Carbon dioxide
CTMs	Chemical transport models
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DTI	Department of Trade and Industry
DU	Dobson Unit
EC	European Commission
$EINO_x$	Emission Indices of NO_x – amount of NO_x emitted (in grams) per kilogram of fuel burnt
EORCU	European Ozone Research Coordinating Unit
FAA	Federal Aviation Administration
GCMs	General circulation models
GDP	Gross domestic product
GWPs	Global Warming Potentials
H_2	Hydrogen
H_2O	Water
HCHO	Formaldehyde
HCs	Hydrocarbons
HNO_3	Nitric acid
HO_2	Hydroperoxy radical
HONO	Nitrous acid
HO_x ($OH + HO_2$)	Hydrogen oxides
HSCTs	High speed civil transports
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
LH_2	Liquid-Hydrogen
LTO	Landing/take off cycle
N_2	Nitrogen
N_2O	Nitrous oxide
NAFC	North Atlantic Flight Corridor

Acronym/Unit	Description
NASA	National Aeronautics and Space Administration
NMHCs	Non-methane hydrocarbons (strictly, only C-H compounds)
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x ($NO + NO_2$)	Nitrogen oxides
O_2	Oxygen
O_3	Ozone
OH	Hydroxyl radical
Pg C yr^{-1}	Petagrams (10^{15}g) of Carbon per year
PM_{10}	Particulate matter that has an aerodynamic diameter of less that 10 μm
ppbv	Parts per billion by volume
ppmv	Parts per million by volume
PSCs	Polar stratospheric clouds
RF	Radiative forcing
RO_2	Peroxy radicals
SASS	Subsonic assessment
SBSTA	Subsidiary Body on Scientific and Technological Advice
SKO	Seat kilometres offered
SO_2	Sulphur dioxide
SPM-TAR	Summary for Policymakers of the Third Assessment Report
SSTs	Supersonic transports
Tg C yr^{-1}	Teragrams (10^{12}g) of Carbon per year
Tg N yr^{-1}	Teragrams (10^{12}g) of Nitrogen per year
UNFCCC	United Nation Framework Convention on Climate Change
USEPA	United States Environmental Protection Agency
UT/LS	Upper troposphere/ Lower stratosphere
UV	Ultra violet
VOCs	Volatile organic compounds (NMHCs plus other organics, e.g. oxygenates)
WMO	World Meteorological Organisation
λ	Climate sensitivity parameter (K $(W\ m^{-2})^{-1}$)

A Box 1 Global Warming Potentials

The GWP is defined as the ratio of the time-integrated radiative forcing arising from the instantaneous release of 1 kg of a trace substance, relative to that of 1 kg of a reference gas (IPCC, 1990), i.e.:

$$GWP_x = \frac{\int_0^{TH} a_x[x(t)]dt}{\int_0^{TH} a_r[r(t)]dt}$$

where TH is the time horizon over which the calculation is made, a_x is the radiative efficiency arising from a unit increase in atmospheric abundance of the substance (x) in question (in W m^{-2} kg^{-1}), [*x*(t)] is the time-dependent decay in the abundance of the instantaneous release of the substance, and r refers to the reference substance in the denominator (IPCC, 2001). Thus, the GWP represents the integrated forcing of a pulse of a substance relative to the same mass emission pulse of a reference gas over the same time-horizon (typically CO_2). The radiative forcings are based upon infrared radiative transfer models that utilize laboratory measurements. Thus, GWPs are suitable for long-lived gases such as CH_4, N_2O and the halocarbons. In the case of aircraft emissions, it is not possible to derive GWPs for particles or their effects. In the case of NO_x emissions, the effect is upon O_3 and is thus *indirect*. The O_3 thus produced is a result of complex atmospheric chemistry and is dependent upon the presence of a range of other chemical species; moreover, the radiative property of O_3 and atmospheric lifetime of O_3 and NO_x is height-dependent. This gives rise to large uncertainties in NO_x and O_3 GWPs.

B Box 2 Chemical production of ozone in the stratosphere and the Chapman Cycle

In the stratosphere, ozone is constantly being formed and photolysed in the Chapman cycle (Chapman, 1930)[130]. At altitudes at above about 30 km, oxygen molecules photodissociate from solar UV at wavelengths less that 242 nm:

$$O_2 \xrightarrow{h\nu} O(^3P) + O(^3P) \quad [1]$$

The ground-state atomic oxygen formed, $O(^3P)$, reacts rapidly with O_2 in the presence of a third molecule (M) to form O_3:

$$O(^3P) + O_2 + M \longrightarrow O_3 + M \quad [2]$$

This is effectively the only reaction that forms O_3 either in the troposphere or the stratosphere. In the stratosphere, the O_3 formed from [2] can strongly absorb UV radiation in the wavelengths > 310 nm, reforming O_2 and $O(^3P)$:

$$O_3 \xrightarrow{h\nu} O(^3P) + O_2 \quad [3]$$

Further, the O_3 from [2] can react with $O(^3P)$ to regenerate two molecules of O_2:

$$O_3 + O(^3P) \longrightarrow 2O_2 \quad [4]$$

These preceding 4 reactions describe Chapman's mechanism for stratospheric production of O_3.

C Box 3 Chemical processes involving ozone in the troposphere

In Box 2, we saw that the main reaction that creates O_3 is the reaction of atomic O with molecular O_2 in a third-body reaction. In the stratosphere, the photolysis of O_2 is the principal source of atomic O. In the troposphere, however, the main source of O(^3P) is from the photolysis of NO_2:

$$NO_2 \xrightarrow{h\nu} NO + O(^3P) \quad [5]$$

Ozone can then be formed by subsequent reaction of O(^3P)(see also Box 2) with O_2, i.e.:

$$O(^3P) + O_2 + M \longrightarrow O_3 + M \quad [6]$$

which may then be destroyed by reaction with NO to reform NO_2:

$$NO + O_3 \longrightarrow NO_2 + O_2 \quad [7]$$

These reactions [5, 6, 7] constitute a 'null cycle' with no net O_3 production and are said to be in steady state, given no extra sources. In order to produce O_3, an alternative reaction to [7] that produces NO_2, without destruction of O_3 is required. For this, the production of the hydroxyl radical is necessary, OH. The hydroxyl radical is formed from the formation of excited atomic oxygen, O(^1D), by photolysis of O_3 at wavelengths < 310 nm, and its subsequent reaction with water vapour, i.e.:

$$O_3 \xrightarrow{h\nu} O(^1D) + O_2 \quad [8]$$

Most of the O(^1D) atoms formed in [8] collide with O_2 or N_2, removing the excess energy quenching it back to its ground state O(^3P), which forms O_3 again through [6]. However, as small fraction of O(^1D) reacts with water vapour to form OH:

$$O(^1D) + H_2O \longrightarrow OH + OH \quad [9]$$

Overall, this is the main source of OH in the atmosphere. However, in the upper troposphere and lower stratosphere, where the atmosphere is poorer in water vapour, photolysis of acetone may be important (Singh *et al*., 1995[131]; Wennberg *et al*., 1998[132]).

Reaction of OH with CO, CH_4 and other non-methane hydrocarbons (NMHCs) can then go on to form the hydroperoxy radical, HO_2; e.g. CO from natural and man-made sources reacts with OH to HO_2:

$$OH + CO \longrightarrow H + CO_2 \quad [10]$$

$$H + O_2 + M \longrightarrow HO_2 + M \quad [11]$$

This HO_2 may then react with NO to form NO_2 which is subsequently photolysed to reform NO, and produce $O(^3P)$, which may then participate in reaction [6]:

$$HO_2 + NO \longrightarrow NO_2 + OH \quad [12]$$

Thus, we have gained a molecule of NO_2, without loss of O_3. In addition, CH_4 and other NMHCs may also contribute to the formation of HO_2:

$$CH_4 + OH \longrightarrow CH_3 + H_2O \quad [13]$$

$$CH_3 + O_2 + M \longrightarrow CH_3O_2 + M \quad [14]$$

$$CH_3O_2 + NO \longrightarrow CH_3O + NO_2 \quad [15]$$

$$CH_3O + O_2 \longrightarrow HCHO + HO_2 \quad [16]$$

NMHCs can also participate as in [13]–[16], where, by convention, the NMHC is designated 'RH', taking the place of CH_4 and its derivative species above. The formaldehyde (HCHO) thus formed can also react with OH to form HO_2 and its photolysis products contribute towards HO_2 formation:

$$HCHO + OH(+O_2) \longrightarrow HO_2 + H_2O + CO \quad [17]$$

$$HCHO \xrightarrow{h\nu} {}^{2}/_{3}\,H_2 + CO \quad [18]$$

and,

$$HCHO + 2O_2 \xrightarrow{h\nu} {}^{1}/_{3}\,2HO_2 + CO \quad [19]$$

Ozone is lost from the system, either by dry deposition at the earth's surface, or by chemical destruction, principally from photolysis to form atomic O, i.e. reactions [3, 8]. Two other major routes of chemical destruction of O_3 are reaction with OH and HO_2

$$O_3 + OH \longrightarrow HO_2 + O_2 \quad [20]$$

$$O_3 + HO_2 \longrightarrow OH + 2O_2 \quad [21]$$

However, any injection of NO competes for the HO_2 therefore reduces the rate of loss of O_3 by HO_x ($OH+HO_2$). Evidently, any NO_x present in the chemical system acts as a catalyst for O_3 production. Nitric oxide also reacts with O_3 to form NO_2, but since the NO_2 is photolysed during the day [5], no net formation of O_3 results on the time-scale of ~1 day except in polar winters. The catalysis is terminated when NO_x is removed from the system, which can occur either in the day by reaction with OH:

$$NO_2 + OH + M \longrightarrow HNO_3 + M \quad [22]$$

or by night to form HNO_3 which is absorbed on existing aerosol:

$$NO_2 + O_3 \longrightarrow NO_3 + O_2 \quad [23]$$

$$NO_3 + NO_2 \longrightarrow N_2O_5 \quad [24]$$

$$N_2O_5 + H_2O \longrightarrow 2HNO_3 \quad [25]$$

However, NO_2 may be regenerated by photolysis of HNO_3:

$$HNO_3 \xrightarrow{h\nu} NO_2 + OH \quad [26]$$

or by reaction with OH,

$$HNO_3 + OH \xrightarrow{h\nu} H_2O + OH \quad [27]$$

and subsequent photolysis of NO_3,

$$NO_3 \xrightarrow{h\nu} NO + O_2 \quad [28]$$

or:

$$NO_3 \xrightarrow{h\nu} NO_2 + O\ (^3P) \quad [29]$$

The role of HO_x is obviously critical. In addition, as mentioned above, acetone ($(CH_3)_2CO$), hydrogen peroxide (H_2O_2) and other peroxides may provide additional sources of HO_x (Wennberg *et al*., 1998)[132]. Peroxy radicals are removed from the system by three main pathways:

$$HO_2 + HO_2 \xrightarrow{M} H_2O_2 + O_2 \quad [30]$$

$$OH + H_2O_2 \longrightarrow H_2O + HO_2 \quad [31]$$

$$\text{Net}: OH + HO_2 \longrightarrow H_2O + O_2 \quad [32]$$

$$OH + NO_2 \xrightarrow{M} NO_3 \quad [33]$$

$$OH + HNO_3 \longrightarrow H_2O + NO_3 \quad [34]$$

$$\text{Net}: 2OH + NO_2 \longrightarrow H_2O + NO_3 \quad [35]$$

$$HO_2 + NO_2 \xrightarrow{M} HNO_4 \quad [36]$$

$$OH + HNO_4 \longrightarrow H_2O + NO_2 + O_2 \quad [37]$$

$$\text{Net}: OH + HO_2 \longrightarrow H_2O + O_2 \quad [38]$$

This Box attempts to describe the basic background photochemistry of the troposphere. There are, however, many more reactions, especially involving organic species that contribute towards the overall control of the oxidising capacity. Such chemistry may be found in standard reference texts such as Seinfeld and Pandis (1998)[61].

D Box 4 Chemical processes involving ozone destruction in the stratosphere

Atmospheric ozone is formed by combination of atomic and molecular oxygen:

$$O(^3P) + O_2 \xrightarrow{M} O_3 \quad [39]$$

Where M is a third body required to carry away the energy and momentum released in the combination reaction.

At altitudes above 20 km, the next O atoms results almost exclusively from photodissociation of molecular O_2 by short wavelength UV radiation:

$$O_2 \xrightarrow{h\nu < 243\,nm} O + O \quad [40]$$

At lower altitudes, especially in the troposphere, O atom formation from photodissociation of NO_2 by long wavelength UV radiation is more important:

$$NO_2 \xrightarrow{h\nu < 400\,nm} NO + O(^3P) \quad [41]$$

In the lower atmosphere, there is a strong coupling between ozone and nitrogen oxides, and ozone production occurs through the reactions discussed in the tropospheric chemistry section.

Ozone in the stratosphere is destroyed predominantly by catalytic cycles involving homogeneous gas-phase reactions of active free radical species

$$X + O_3 \longrightarrow XO + O_2 \quad [42]$$

$$XO + O \longrightarrow X + O_2 \quad [43]$$

$$\text{Net}: O + O_3 \longrightarrow O_2 + O_2 \quad [44]$$

Where the catalyst X is H, OH, NO, Cl and Br.

The balance between the production and destruction of ozone is established rapidly on time scales of less than 1 day in the upper stratosphere. At lower altitudes the chemical processes slow down and below altitudes of 25 km the local concentration of ozone is determined primarily by transport.

In the lower stratosphere and the troposphere, coupling of the NO chemistry with HO_x chemistry and CO oxidation, gives rise to the net production of O_3:

$$HO_2 + NO \longrightarrow NO_2 + OH \quad [45]$$

$$OH + CO + (O_2) \longrightarrow CO_2 + HO_2 \quad [46]$$

$$NO_2 \xrightarrow{hv} NO + O \quad [47]$$

$$O + O_2 \xrightarrow{M} O_3 \quad [48]$$

$$\text{Net} : CO + 2O_2 \longrightarrow CO_2 + O_3 \quad [49]$$

The change from net O_3 production to net ozone destruction resulting from NO_x chemistry, occurs in the lowermost region of the stratosphere. The location of this changeover however is dependent upon latitude and season.

Interaction between the radicals can result in the formation of reservoir species. For example, the HO_x and NO_x families are coupled through the reaction:

$$OH + NO_2 \xrightarrow{M} HNO_3 \quad [50]$$

Active nitrogen species are slowly regenerated by photolysis or reaction with OH:

$$HNO_3 \xrightarrow{hv} OH + NO_2 \quad [51]$$

$$OH + HNO_3 \longrightarrow H_2O + NO_3 \quad [52]$$

Similar mechanisms for the formation of reservoir species occurs between the HO_x, NO_x, ClO_x and BrO_x species.

Emissions of NO_x from aircraft may therefore act to decrease the efficiency of ozone loss by accelerating the formation of reservoir species.

Distribution list

Dr Helen L. Rogers, EORCU, University of Cambridge
Prof. David S. Lee, QinetiQ
Dr David Raper, Manchester Metropolitan University
Dr Piers M. D. de F. Forster, The University of Reading
Prof. Christopher Wilson, QinetiQ
Mr Peter J. Newton, Department of Trade and Industry

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Mr Martin Wedlock, QinetiQ
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10a. Abstract. (An abstract should aim to give an informative and concise summary of the report in up to 300 words).

This paper provides the current status of knowledge regarding the impact of aviation on the atmosphere. The growth of the aviation industry is likely to continue in the future and at present there are significant concerns that this will adversely affect climate and local air quality in the vicinity of airports. Indeed, it is possible that air quality may become a constraint to increased capacity of some large hub airports. Currently the radiative forcing impact from aircraft emissions, other than CO_2, are not accounted for in the International Civil Aviation Organization emission trading scheme proposals. Taking only this approach, emissions trading could, in theory, increase the radiative forcing, rather than decrease it. The study of improved 'environmentally friendly' flight is still in its infancy, however any proposed and actual new developments, in terms of technology and operational practice, should include an environmental assessment.

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