Aviation Impacts on the Atmosphere

A Report of the Town Meeting organised by NCAS, and held at Birkbeck College, London, 11th and 12th November 2004

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Executive Summary

On an initiative taken by the academic community, a ‘Town Meeting’ was organized under the auspices of the NERC Centres for Atmospheric Science, in collaboration with Manchester Metropolitan University and the University of Cambridge. Approximately 60 scientists and engineers attended from UK academia, giving a broad representation of the expertise from universities that have interests in this field. Seven plenary talks were given that covered recent and current assessments, climate science, engine/airframe engineering, local air quality, atmospheric chemistry and UK/international policy drivers. Breakout groups were asked to address research requirements and prioritize them. These were then reported back and discussed within a plenary session. This document represents a synthesis of the two-day meeting presentations, discussions, conclusions and recommendations. It provides brief updates on the science and conclusions and recommendations for future research. It was concluded that there are three research priorities that need addressing: local air quality; global climate and atmospheric composition; engine, airframe and fuel technology developments. Whilst not discussed extensively, the meeting concluded that relevant socio-economic research was also important with the requirement to look more deeply into the economics of the industry. We conclude that there is considerable expertise available within the UK academic sector that can address the research requirements identified – much of this research not only addresses the impacts of aviation on the atmosphere but also supports much-needed basic scientific research where there are key uncertainties in atmospheric processes.

1 Background

Market pull is set to demand an increase in aviation traffic, which, if satisfied will lead to a four fold increase in annual fuel burn over the next 20 years, and a doubling in the number of aircraft (25,000). This is a significant UK policy issue not least because currently 20% of all international air passengers in the world are on flights to or from a UK airport. If international aviation emissions were included in domestic emissions inventories, aviation’s proportion of total UK

CO_2 emissions in 2050 would be ~35% according to Department for Transport estimates, and much higher than that as a proportion of radiative forcing.

The Intergovernmental Panel on Climate Change (IPCC)'s Special Report 'Aviation and the Global Atmosphere', published in 1999, addressed many of the issues related to aviations impact on climate. However, since the publication of this report, this topic has received attention from the Royal Commission on Environmental Pollution and featured in the recent Department for Transport Air Transport White Paper.

Moreover, research has been committed, internationally, to determining aviation's impacts, particularly through the European Fifth Framework Research Programme (5FP) in projects that include: TRADEOFF, PARTEMIS, AERO2K, SCENIC, NEPAIR etc. These projects have now finished and many of the results were presented at a major international meeting in Friedrichshafen, in 2003 (Sausen *et al.*, 2004). Nonetheless, many issues remain open in terms of quantifying the impacts of aviation on both climate and air quality and potentially reducing the impacts through technological improvement and operational procedures.

Given this backdrop of unresolved issues, the importance of aviation to the global economy and the tensions between a growing industry and environmental sustainability, NCAS organized a workshop of scientists and engineers from academia to discuss and prioritize possible areas of future research. The UK has significant expertise in atmospheric science and engineering which could be utilised to address the impact of aviation on the atmosphere if funding became available.

The aim of this paper is to provide a concise summary of the main physical science and engineering uncertainties that need to be addressed based upon the outcome of the NERC/NCAS Town Meeting on 'Aviation Impacts on the Atmosphere' held on 11/12 November 2004.

2 Meeting structure and objectives

Seven presentations were made during the plenary session of the NCAS Town Meeting:

1. '*The Environmental Effects of Civil Aircraft in Flight – An Assessment by the Royal Commission on Environmental Pollution (RCEP)*' – Professor Roland Clift, University of Surrey
2. '*Research on climate effects of aircraft and IPCC perspective on the issues*' – Dr Piers Forster, University of Reading (CLA of forthcoming radiative forcing chapter from AR4, WG1)
3. '*Impact of aviation on atmospheric composition; including laboratory studies and observations*' – Professor John Pyle, University of Cambridge
4. '*Modelling the impacts of aviation on local air quality: data and modelling constraints*' – Professor David Raper, Manchester Metropolitan University
5. '*Prospects for reducing fuel burn through aircraft design and application of advanced technology*' – Professor Ian Poll, Cranfield University
6. '*Policy drivers for aviation emissions research*' – Mr Roger Gardner, Department for Transport
7. '*Impacts of aviation and other transport modes on the atmosphere: A European perspective*' – Dr Terje Berntsen, University of Oslo

These presentations may be accessed through the NCAS web link[1]. In addition to these presentations, break out groups were tasked with producing a prioritized list of specific research problems that need to be addressed considering: local air quality; climate change; atmospheric composition; engine/aircraft design; and socio-economic issues.

The physical science and engineering issues associated with impacts of aviation on the atmosphere fall under four headings:

- Local air quality around airports (noise is also an environmental issue but is not considered here)
- Atmospheric composition changes from aviation emissions
- Radiative forcing and climate change associated with emissions by aircraft in flight
- Engine, airframe and fuel technology developments

There are strong interdependencies between these four areas but it is helpful in covering the range of issues to discuss them individually. Also there is a range of socio-economic issues connected with aviation (including both passenger and freight transport) - the Town Meeting made clear that these are important and that they would need to be included in any new programme on the subject, however they are not discussed in detail here.

3 Research Issues

3.1 Local Air Quality Around Airports

Urban air quality is a major area of current research in its own right. Current knowledge suggests that the principle problem of local air quality in and around airports is the level of NO_2. High quality measurements reveal enhanced levels of nitrogen dioxide on and around airports – with current annual mean concentrations of 50 $\mu g\ m^{-3}$ near Heathrow – higher levels than upcoming European legislation will permit. Other pollutants including PM_{10}, CO and O_3 do not generally approach levels that exceed UK and European air quality standards. However, air quality standards should not necessarily constrain research. The particles emitted from aircraft exhaust are small (*nm* scale) and in terms of mass may not exceed the air quality standards. However, from a health perspective, it is likely that particle number may have a stronger correlation with adverse health effects. In such a case, it would be important to characterize the nature (volatile/non volatile), size, number density and chemical composition of such particles emitted from aircraft exhaust. Precise characterisation of engine emissions during taxi, landing and take-off is therefore needed particularly of the speciated hydrocarbons and particles, including nano-particles.

One of the principle uncertainties in modelling NO_2 in the vicinity of airports is attribution, due to the uncertainties in parametrising the behaviour of aircraft plumes. Vertical and horizontal movement of pollutants is dictated by atmospheric dispersion and turbulence. Aircraft have a very particular effect on dispersion and turbulence through the aircraft wake and vortices (after take-off). There is currently considerable interest in the precise characteristics of the plume,

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[1] http://ncas.nerc.ac.uk/meetings/past/aviation_impacts/aviation_impacts_mtg.asp

including the vortices, since this will have a large effect on the contribution of aircraft emissions to local air quality.

Although O_3 levels are often reduced around airports (due to elevated NO concentrations which may reduce ambient O_3), this does not necessarily imply that airports do not contribute to enhanced levels of boundary layer O_3. Such enhancements would be expected some tens of kilometres downwind of the airport and as such, are only likely to be attributed through appropriate modelling techniques. Improved modelling of pollutants in the vicinity of the airport is required in order to predict the location and frequency of high pollution concentrations under varying meteorological conditions. A local air quality model either has to link with or include a meteorological model together with complex chemistry if photochemical oxidants are to be addressed on a larger scale. The evaluation of such improved models will require extensive measurements in and around airports and may include a series of campaigns. An ongoing need to monitor key pollutants on a semi-continuous basis is also required to determine local air quality and to provide input into local air quality models.

Overall, it is clear that little progress has been made in recent years to model the particular environment of the airport in terms of pollutant emission (e.g. APU[2] emissions), including characterization of the dispersion of aircraft plumes. Furthermore, there may be emerging issues over the importance of some of the pollutants (e.g. emissions of PAHs, some of which may be carcinogenic, have not been adequately characterized).

It is clear that airports are major transport hubs and will inherently have a higher than average ground transportation density which, in turn, will also strongly influence the local air quality. Major airports are often close to urban areas and will consequently provide a contribution to determining the overall urban air quality. It is now clear that NO_2 emissions in particular may hinder the growth of some airports and as such the issues outlined above represent critical knowledge gaps for assessing the contribution of aircraft to local air quality.

3.2 Atmospheric Composition Changes from Aviation Emissions

There have been various influential reports and studies on the impacts of aviation on atmospheric composition and climate change: the IPCC Special Report on Aviation in 1999, the Royal Commission on Environmental Pollution Report in 2002 and an EU research project TRADEOFF completed in 2003. We do not aim to re-iterate here the various mechanisms that have been examined but rather summarise the important uncertainties that yet remain to be quantified.

There are two aspects to the science – estimating the role of aviation on current atmospheric composition and climate change, and estimating its role in the future as climate change, from anthropogenic forcing, occurs and the projected growth in aviation transpires.

The transport and chemical transformation of pollutants from aviation in flight can have a local and remote effect on the atmosphere including ground-level air quality. As the chemistry of the troposphere, in particular, is complex and as yet far from being fully understood, this aspect of

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[2] Auxiliary Power Units – a smaller power gas turbine that provides the aircraft with power, often located at the end of the fuselage

aviation's impact on the atmosphere is associated with large uncertainties, with the potential for producing a significant environmental effect. A key aspect is the role of ozone in changing the oxidising capacity of the atmosphere, which acts as a way of cleansing the atmosphere of pollutants. Many of the chemical reactions have poorly characterised reaction rates and one key requirement is to reduce these uncertainties by using state-of-the-art laboratory techniques. Current models, which aim to describe the dynamics and chemistry of the atmosphere need to be improved with particular emphasis on increased horizontal and vertical resolution. The description of the upper troposphere lower stratosphere in these models is crucial since mixing across the tropopause is critical in transferring species between these two chemically and radiatively distinct regions of the atmosphere.

The models have improved dramatically since the research presented by the IPCC (1999), however, the assessment of models within the TRADEOFF project made clear that there is still much research to do. Previously, three dimensional global chemical transport models (CTMs) tended to consider the troposphere or stratosphere in isolation, with only a few considering both regions (although even these were subject to limitations). Moreover, most chemical models were 'offline' (driven using meteorology derived from global climate models or assimilated observations) and therefore were unable to consider any feedback from chemical/radiative perturbations on the dynamics. More refined offline CTMs are still required, that properly treat both the troposphere and stratosphere in terms of chemistry and dynamics together with fully coupled chemistry-climate models.

Aircraft emissions include NO_x (currently 0.7 Tg N/year, with an expected increase to 2.1 Tg N/year by 2050), which at cruise altitudes in the upper troposphere/lower stratosphere, can lead to ozone formation. Recent modelling studies have shown that the ozone perturbation from current aviation is ~6% of the total atmospheric ozone column (or 9 ppb), increasing to a value of 12% in 2050 (or 18 ppb). These increases are mainly in the upper troposphere. Note that from all anthropogenic sources the tropospheric ozone column concentrations are expected to increase by about 30% from 2000 to 2050 with aviation contributing 5% of this rise. These 2050 estimates are based upon what are now dated emissions scenarios. Revised emissions scenarios are required that reflect both recent changes in the industry, new aircraft and underlying socio-economic assumptions (i.e. SRES c.f., the older IS92 scenarios).

Production of ozone at cruise altitudes leads to the destruction of carbon monoxide in the upper troposphere. As a result of these changes, the reduced transport of CO and increased transport of ozone, to lower altitudes and latitudes, both lead to an increased generation of OH and an associated reduction in methane. The transport of pollutants throughout the atmosphere from source regions, typically in the mid-latitude tropopause region, makes evaluation of the perturbation to the atmospheric composition from aviation difficult and the subject of much needed further research. Recent results from TRADEOFF modelling suggest that the reduction of CH_4 (an important radiatively active gas) might be less than that previously calculated with lower resolution models: however, this remains to be properly quantified.

The downward transport of ozone from the upper troposphere lower stratosphere source region to the surface is again a major area of uncertainty. The role of weather systems, e.g., fronts and convection, in this transport and mixing remains largely unresolved due to the relatively coarse resolution within current models. A recent study (Tarrason et al., 2004) has shown that non-LTO emissions might make a significant contribution to boundary layer pollution (particularly O_3). However, the results are strongly dependent upon the details of the vertical mixing assumed in such models, which is generally parameterized quite crudely and is often model-scale dependent. Further research on both cross-tropopause and convective transport is required before we can expect convergent results and reliable assessments of aircraft impact of NO_x.

3.3 Radiative forcing and climate change associated with emissions by aircraft in flight

Total aviation radiative forcing and its contribution to that from the transportation sector

Aside from the effect of aviation emissions upon the physical and chemical composition of the atmosphere, these emissions are also important in the radiative forcing of climate.

The total radiative forcing (RF) attributable to aviation for the year 1992 (not including the highly uncertain but potentially significant contribution from aviation-induced cirrus) has been evaluated by IPCC to be 48.5 mW m^{-2}; if this scaled by increases in traffic to the year 2000, it would be ~71 mW m^2. The TRADEOFF project updated these calculations for 2000 and gave an RF (again, excluding cirrus RF) of 47.8 mW m^{-2} (Sausen *et al.*, 2005). Berntsen at the NCAS Town Meeting presented a provisional assessment of the total RF from the whole transportation sector of ~200 m Wm^{-2}; indicating a contribution from aviation of ~24%. By 2050 it is anticipated that the radiative forcing from aviation might have risen by a factor of ~4-5 from 2000 levels.

Contrail radiative forcing

Recent studies have shown that the radiative forcing from contrails is potentially smaller than estimated by the IPCC. The IPCC (based upon Minnis *et al.*, 1999) calculated a forcing of 20 mW m^{-2} for 1992. Recent estimates have ranged from 3.5 to 15 mW m^{-2} (Marquart and Mayer, 2002; Mhyre and Stordal, 2001). The estimate of contrail radiative forcing for 2000 provided from the TRADEOFF project was 10 mW m^{-2} (Sausen *et al.*, 2005).

The linkage between the observed changes in the diurnal temperature range over the USA with the elimination of contrails over the USA post 9/11, when aircraft operating over the USA were grounded, remains controversial. This is primarily because of the difficulty in eliminating the role of other factors such as natural meteorological variability. This event has therefore a symbolic significance but probably not much scientific significance as it is a single, possibly unrepresentative, event. That contrail coverage was reduced is obvious and quantifiable: what is not easily attributable is the change in diurnal temperature range – the consequence of contrail RF.

Cirrus cloud coverage and radiative forcing

In contrast to RF from contrails, the RF from aviation induced cirrus calculated in the TRADEOFF project had a *larger* upper bound of 50 mW m^{-2} (Stordal *et al.*, 2005) than the 40 mW m^{-2} previously estimated by IPCC. Minnis *et al.* (2004) have recently estimated a combined contrail and cirrus RF of ~25 mW m^{-2}.

Large uncertainty remains: the analyses of, for example, Zerefos *et al.* (2003) and Stordal *et al.* (2005) were advances over the IPCC analysis (which was more rudimentary), providing much better data-based quantification of potential cirrus cloud cover enhancement from air traffic – however, little effort has yet been committed to linking observations of contrails and cirrus to aircraft movements on a dynamic basis. Further research is required in order to determine a robust estimate of the cirrus forcing.

Operational measures to reduce contrail (and cirrus) radiative forcing

In principle, contrails can be strongly reduced or even eliminated by routing aircraft away from the generation 'zones' in the atmosphere since environmental parameters of temperature and ice-supersaturation largely control the production of contrails. Simplified modelling studies have demonstrated that by lowering the overall cruise altitude of the global fleet by 6,000 ft, it is possible to reduce contrail coverage and RF by 43 and 47%, respectively for an increase in CO_2 emissions of ~6% (Fichter *et al.*, 2005). Clearly, a more refined solution is possible via selective routing/altitude changes since the critical parameters for contrail production can vary over one flight level (now 1,000 ft for large parts of Europe) and a horizontal scale of 10 – 100 km.

It is feasible to predict, using weather forecast models, where these 'zones' are likely to occur several hours in advance although the skill of such forecasts has not been extensively evaluated. It is also feasible to include instruments for on-board detection of contrails that might allow in-flight course correction for avoidance of such zones. The economic and logistical implications of such a system should not be underestimated. Thus it is critical to determine whether contrails are the highest priority impact to be targeted. This may be questioned, given the recent downward projections of contrail RF. However, it should be remembered that according to current understanding, dispersed persistent contrails enhance cirrus cloudiness. It is also theoretically possible to produce enhanced cirrus cloudiness in the absence of contrails, when the emitted exhaust particles encounter the appropriate conditions of temperature and ice-supersaturation, some time after the emission. It is therefore possible that, even if contrails were eliminated by re-routing, a reduction and/or modification of cirrus clouds would not necessarily occur.

Cirrus clouds can also have a significant effect on the greenhouse effect. Daily averaged predictions of radiative forcing suggest that overall they cause a warming effect (with enhanced warming at night being offset slightly by cooling during the day due to increased planetary reflectance). Large uncertainty however remains as to the cloud microphysical processes that could, in principle, suggest that cirrus formation is related indirectly to particulates from aircraft emissions.

Limitations and characteristics of the radiative forcing metric

Whilst radiative forcing is extensively used as a climate metric, it has its limitations (Fuglestvedt *et al.*, 2003). The temperature response of some aircraft-induced perturbations, e.g. O_3 in the upper troposphere-lower stratosphere (UTLS), might be rather different, as has been found in the

EU 'METRIC' project (Joshi *et al.*, 2004). This arises from differences in the climate sensitivity parameter, which is rather poorly quantified for some of the aviation-specific effects. Moreover, the definition of RF involves a global average and regional variations in forcing are not captured. It is suggested that a range of new metrics are required to allow a more useful assessment of the role of aviation on climate change.

As discussed above aircraft emissions of NO_x, at cruise altitudes in the UTLS can lead to ozone formation. These increases are mainly in the upper troposphere and are thought to increase surface global warming by perhaps 0.005°C per 10% ozone increase. This is only a small contribution to global warming - although it should be noted that calculations for 2050 (which predicted an increase in ozone of 12%) have only been carried out using atmospheric conditions typical of 1995 and therefore do not include the other anthropogenic climate changes expected to occur by 2050.

The importance of climate impact quantification in regulatory measures

Radiative forcing from aircraft have a total effect of approximately three times that which would be associated purely with aviation radiative forcing of CO_2 alone according to the IPCC – although this (the Radiative Forcing Index) has been revised to approximately two by Sausen et al. (2005) from the TRADEOFF project. When taking measures to limit the impact of aviation on climate the non-CO_2 forcings should ideally be taken into account (Lee and Sausen, 2000). For example, technological improvements aimed at improving fuel efficiency (and thereby reducing CO_2 emissions) tend to increase NO_x emissions – increasing the $EINO_x$[3] because of the higher overall pressure ratios and increased combustor temperatures and pressures required. However, radiative forcing alone cannot assess the climate role of emissions as it does not consider the timescale over which the aviation emissions will influence climate. For example CO_2 emissions give a radiative forcing lasting several decades, in contrast to contrails which only last a few hours. The same emissions in different geographical locations can also have quite different climate impacts. It is desirable that new metrics be developed to quantify and contrast these climate impacts of aircraft emissions. These metrics would be needed if the non-CO_2 forcings from aviation were to be included in any emission trading scheme.

In general improved regional and global assessments of the impact of aviation on climate change are required, that allow for not only the anticipated increase in aviation traffic but also the changes to climate that are expected from other sources. This will require improved predictions from coupled chemistry-climate models using higher resolution than at present with improved complex chemistry.

3.4 Engine, airframe and fuel technology developments

Possible technological solutions to the environmental issues associated with aviation can be divided into airframe, engine and operational aspects. Operational aspects at cruise altitudes are dealt with in sections 3.2 and 3.3. It is worth noting that the NO_x produced by aircraft engines is related to the operating temperature, whilst CO_2 and water vapour emissions are dependent upon both the type and the amount of fuel burnt (hydrogen fuel would produce no CO_2 for example in

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[3] $EINO_x$ – emissions index of NO_x, i.e. g NO_x/kg fuel

the aero engine but would lead to CO_2 emissions elsewhere in the fuel supply chain). If current maximum operating temperatures were to be reduced to around 2100 K most of the NO_x production would be eliminated. Contrails can also be avoided by flying higher or lower, or re-routing according to weather forecasts of the location of contrail-susceptible regions, as discussed previously. However, the retention of optimum fuel burn rates at lower altitudes would require slower flying speeds thus slightly increasing journey times, although this may not be significant.

Technology has provided options for reducing emissions from aviation, however there is a *trade-off* to be made between the different pollutants (including noise). Determining the optimised design and operation of an aircraft in order to produce a minimal environmental impact, both in terms of atmospheric composition and climate change, will be critical for future aviation technology. This cannot be achieved within either the technology or science communities alone but requires a combined effort to optimise different technologies for different operational scenarios under present and future atmospheric conditions.

Designs for engines, airframes (e.g. blended wing body) and operational procedures are currently being developed and assessed, however, research into their potential atmospheric impacts is urgently required.

4 Conclusions and Recommendations

- Aviation is a strongly growing and economically important sector. Air quality constraints around airports are already representing potential barriers to growth.

- Aviation impacts on local air quality, noise and climate – the technology that affects these impacts has tradeoffs and such constraints need to be understood in any scientific discussion.

- Upper atmosphere emissions are currently unregulated. However, emissions' trading has been suggested as a possible policy measure for aviation CO_2 emissions but this requires careful assessment of climate impacts if environmental integrity is to be achieved. This implies both scientific and policy research.

- Whilst aviation represents 2% of global CO_2 emissions at present, it is its expected strong growth against a backdrop of falling emissions from other sectors that makes scientific quantification of its impacts a policy-relevant issue.

- Research efforts need to focus on two aspects: better and more robust quantification of the impacts of aviation and the possibilities that improved technologies (engine, airframe, operational) might offer through analysis of environmental impacts as a combined technology/science programme.

We recommend that the following areas need to be the subject of further research in order to quantify impacts and investigate possibilities for minimising the impact of aviation on the atmosphere. We have identified three main areas, with equal priority; within each area an attempt is made to prioritize the research although this is somewhat subjective.

Local air quality: measurement and modelling of the plume structure (and composition), wake vortices and its dispersion. Formulation of suitable validated and tested air quality models that incorporate adequate parameterization of plume processes. Measurements of aircraft emissions with microphysical and chemical characterization.

Global climate and atmospheric composition: formulation and testing of both offline chemistry transport models and coupled chemistry-climate models – this is essentially the continuation of an existing research path, which has not yet reached maturity. Equally weighted is the measurement and analyses of contrail/cirrus cloud interactions using both local and remote sensing techniques; assimilation of methods into models that predict contrail and cirrus cloud enhancement. Further assessment is needed of the suitability and sensitivity of different climate metrics to quantify aviation's impacts. Long term monitoring of atmospheric constituents, particularly those of importance to climate change. Laboratory studies of chemical kinetic reaction rates applicable to aviation's impact.

Engine, airframe and fuel technology developments: This aspect should focus on bilateral research programmes between engineers and scientists such that new engine/aircraft configurations can be analysed using improved atmospheric models in order to determine the tradeoffs that might exist with new engine/airframe technologies and operational procedures.

References

Fichter, C., Marquart S., Sausen R. and Lee, D.S., 2005: The impact of cruise altitude on contrails and related radiative forcing. *Meteorologische Zeitschrift* (accepted, under revision).

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

IPCC (1999) Aviation and the global atmosphere - A special report of IPCC working groups I and III. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK

Joshi, M., Shine, K., Ponater, M., Stuber, N., Sausen, R. and Li, L., 2003: A comparison of climate response to different radiative forcings in three general circulation models: towards an improved metric of climate change. *Climate Dyn. 20*, 843-854.

RCEP (2002) The Environmental Effects of Civil Aircraft in Flight – a Special Report of the Royal Commission on Environmental Pollution.

Lee., D.S. and Sausen, R., 2000: New Directions: Assessing the real impact of CO_2 emissions trading by the aviation industry. *Atmos. Environ. 34*, 5337-5338.

Marquart, S. and Mayer, B., 2002: Towards a reliable GCM estimation of contrail radiative forcing. *Geophys. Res. Lett. 29***,** 1179, doi: 10.1029/2001GL014075.

Minnis, P., Schumann, U., Doelling, D.R., Gierens, K. and Fahey, D.W., 1999: Global distribution of contrail radiative forcing. *Geophys. Res. Lett. 26***,** 1853–1856

Minnis, P., Ayers, J.K., Palikonda, R. and Phan, D., 2004: Contrails, cirrus trends, and climate. *J. Clim. 17*, 1671-1685.

Myhre, G., and Stordal, F., 2001: On the tradeoff of the solar and thermal infrared radiative impact of contrails, *Geophys. Res. Lett. 28*, 3119-3122.

Sausen, R., Fichter C. and Amantides G. (eds) (2004) European Conference on Aviation, Atmosphere and Climate (AAC), proceedings of an international conference, Friedrichshafen, Germany, 30th June to 3rd July, 2003. Air Pollution Research Report no. 83. Eur 21051 (see http://www.pa.op.dlr.de/aac/proceedings.html).

Sausen, R., Isaksen I., Grewe, V., Köhler, M., Lee D. S., Myhre G., Schumann U., Stordal F., and Zerefos C., 2005: Aviation radiative forcing in 2000: an update on IPCC (1999). *Meteorologische Zeitschrift* (accepted, under revision).

Shine, K.P., Fuglestvedt, J., Hailemariam, K. and Stuber, N., 2004: Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change* (in press).

Stordal, F., Myhre, G., Arlander, D.W., Svendby, T., Stordal. E.J.G., Rossow, W.B. and Lee, D.S., 2005: Is there a trend in cirrus cloud cover due to aircraft traffic? *Atmos. Chem. Phys.* (accepted, under revison).

Tarrasón, L., Jonson, J.E., Berntsen, T.K. and Rypdal, K. (2004) Study on air quality impacts of non-LTO emissions from aviation. Final Report to European Commission, Contract no. B4-3040/2002/343093/MAR/C1.

Zerefos, C.S., Eleftheratos, K., Balis, D.S., Zanis, P., Tselioudis, G., and Meleti, C., 2003: Evidence of impact of aviation on cirrus cloud formation. *Atmos. Chem. Phys. 3*, 1633-1644.