20

ISSUES IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY

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Transport and the Environment

Issues in Environmental Science and Technology

editors R.E. HESTER and R.M. HARRISON

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Preface

Mass transportation has become central to the lifestyle of developed societies. Long-distance commuting to work has become commonplace, and commerce requires ever greater amounts of transport capacity for goods over ever increasing distances. Alongside these trends, the advent of low-cost air travel has led to a massive increase in passenger mileage. Inevitably, such developments have consequences for the environment and, ultimately, also for human health.

Air transport is one of the fastest growing transport sectors and subsonic aircraft operate, typically, in the upper troposphere where their emissions can have an appreciable impact. David Lee reviews the contribution of aircraft to global pollution and examines some aircraft-specific phenomena such as contrail formation that have a direct impact on climate forcing. In the second chapter, Dick Derwent takes a forward look at the possible consequences of a future hydrogen economy, which is seen by some experts as a panacea largely without adverse environmental consequences. This chapter takes a dispassionate look at the effects of increasing the use of hydrogen as a fuel upon atmospheric chemistry and how this will impact upon climate. The overall conclusion, however, is that the climatic effects of a hydrogen economy will be much smaller than those of the carbon economy it may replace and, at least in respect of climate impacts, this is rather reassuring.

An ultimate aim of policy should be to render mass transport sustainable. A valuable tool in assessing progress towards sustainability is the performance indicator, which can be used as a measure of progress. However, devising such indicators is by no means straightforward and in the third chapter Henrik Gudmundsson explains the complexities of devising performance indicators for sustainable transport and reviews some of the more important activities to date. Perhaps even more problematic is the development of policy instruments for achieving sustainable transport. Most members of society have a strong belief in reducing car use, but a much lesser enthusiasm for reducing their use of their own car. Inevitably, reductions in car use will only be effected as a result of the introduction of policy instruments such as the congestion charging introduced recently in central London. In the fourth chapter David Begg, who is well known as a transport adviser to the UK government, and David Gray discuss the policy instruments that could be applied and their likely effectiveness.

Transport, especially in the form of road vehicles, contaminates not only the atmosphere but also surface waters. In the next chapter, Mike Revitt examines how traffic is responsible for a wide range of pollutants that subsequently enter and cause deterioration of the quality of surface waters. This is an area where a good deal of specific case study information is available. Engineering controls can be developed but only at considerable expense.

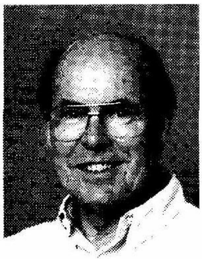
Evaluation of climate change as a result of changes to radiative forcing brought about by greenhouse gases and other atmospheric constituents can currently only be evaluated through the use of computationally intensive global circulation models. One of the major centres for research on climate change is the Max Planck Institute (MPI) for Meteorology in Hamburg, and Martin Schultz, Johann Feichter, and Jacques Leonardi of the MPI have contributed a chapter on climate impacts of surface transport, in which they evaluate the contribution of surface forms of transport to greenhouse emissions and the consequent effects on the atmosphere.

Whilst greenhouse gases have little direct effect on human health, there is ample evidence that other pollutants generated by combustion can have very significant effects on the health of human populations. In the final chapter, Roy Harrison and Stephen Thomas examine the contribution of the various surface transport options to emissions of locally acting air pollutants and review the evidence that those pollutants are having an impact upon public health. Specific studies of the health effects of living in close proximity to major roads are also considered.

This volume of *Issues* represents an important collection of papers on the major aspects of the subject from authors with international reputations for their research in the field. As such, it presents an authoritative review of the current state of knowledge that should prove of lasting value to scientists, policymakers and students on environmental science and engineering courses.

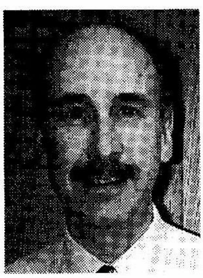
Roy M. Harrison
Ronald E. Hester

Editors



Ronald E. Hester, BSc, DSc(London), PhD(Cornell), FRSC, CChem

Ronald E. Hester is now Emeritus Professor of Chemistry in the University of York. He was for short periods a research fellow in Cambridge and an assistant professor at Cornell before being appointed to a lectureship in chemistry in York in 1965. He was a full professor in York from 1983 to 2001. His more than 300 publications are mainly in the area of vibrational spectroscopy, latterly focusing on time-resolved studies of photoreaction intermediates and on biomolecular systems in solution. He is active in environmental chemistry and is a founder member and former chairman of the Environment Group of the Royal Society of Chemistry and editor of 'Industry and the Environment in Perspective' (RSC, 1983) and 'Understanding Our Environment' (RSC, 1986). As a member of the Council of the UK Science and Engineering Research Council and several of its sub-committees, panels and boards, he has been heavily involved in national science policy and administration. He was, from 1991 to 1993, a member of the UK Department of the Environment Advisory Committee on Hazardous Substances and from 1995 to 2000 was a member of the Publications and Information Board of the Royal Society of Chemistry.



Roy M. Harrison, BSc, PhD, DSc(Birmingham), FRSC, CChem, FRMetS, Hon MFPH, Hon FFOM

Roy M. Harrison is Queen Elizabeth II Birmingham Centenary Professor of Environmental Health in the University of Birmingham. He was previously Lecturer in Environmental Sciences at the University of Lancaster and Reader and Director of the Institute of Aerosol Science at the University of Essex. His more than 300 publications are mainly in the field of environmental chemistry, although his current work includes studies of human health impacts of atmospheric pollutants as well as research into the chemistry of pollution phenomena. He is a past Chairman of the Environment Group of the Royal Society of Chemistry for whom he has edited 'Pollution: Causes, Effects and Control' (RSC, 1983; Fourth Edition, 2001) and 'Understanding our Environment: An Introduction to Environmental Chemistry and Pollution' (RSC, Third Edition, 1999). He has a close interest in scientific and policy aspects of air pollution, having been Chairman of the Department of Environment Quality of Urban Air Review Group and the DETR Atmospheric Particles Expert Group as well as a member of the Department of Health Committee on the Medical Effects of Air Pollutants. He is currently a member of the DEFRA Air Quality Expert Group, the DEFRA Advisory Committee on Hazardous Substances and the DEFRA Expert Panel on Air Quality Standards.

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The Impact of Aviation on Climate

DAVID S. LEE

1 Introduction

The atmospheric impact of aviation falls into two distinct categories: those upon the global atmosphere and those upon local air quality. Further, the impact upon the global atmosphere can be subdivided between climate change and stratospheric ozone (O_3) depletion. The latter has only been studied from a hypothetical point of view, since this is a potential effect that might arise from a fleet of supersonic aircraft flying in the mid stratosphere. This chapter will focus on the effects of aviation on the global atmosphere and, in particular, climate change. Whilst the scientific understanding of aviation's impacts on air quality is reasonably well understood, specific details that allow robust assessments of aviation impacts on local air quality — perhaps surprisingly — are only poorly quantified and the reader is directed elsewhere for a brief overview.[1]

Interest in aviation's effects on climate has been provoked by the strong growth of the aviation industry, which has outstripped GDP, long-term growth rates of the order 5% per year being sustained. Particular events have been associated with set-backs to this growth: the Gulf conflict in the early 1990s slowed growth but it picked up quickly and returned to the long-term trend within a few years. More recently, the overall economic downturn of the industry, September 11th, and 'SARS' have taken their toll but there are indications that growth rates are recovering. The seasonal patterns of departures between 1997 and 2003 in Europe (Figure 1) provide evidence of this.

Many forecasts of aviation growth have been made, both by the industry and others; typical is that of the UK Department of Trade and Industry (Figure 2), which shows historical and future projected growth to 2020 in terms of the overall capacity.

In developing this overview, and what current research is telling us, it is worth considering some historical aspects — the origins of interest date back perhaps

[1] H. L. Rogers, D. S. Lee., D. W. Raper, P. M. de Forster, C. W. Wilson and P. J. Newton, *Aeronaut. J.*, 2002, **106**, 521.

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Figure 1 Monthly departures within the Eurocontrol air traffic region, 1997–2003 (data Eurocontrol, personal communication)

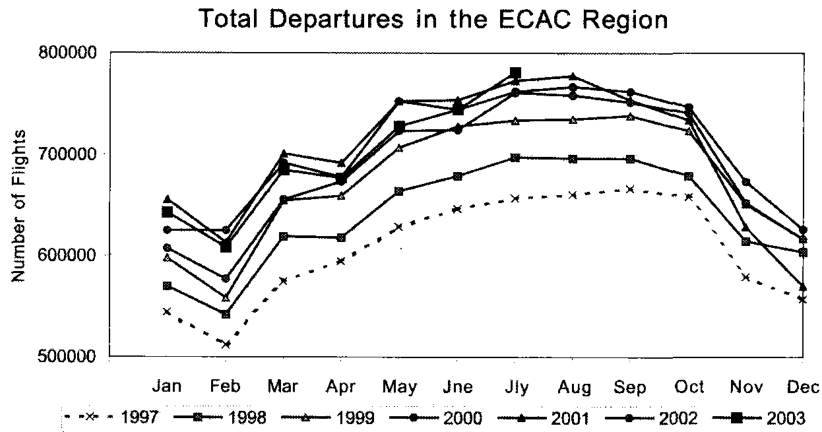
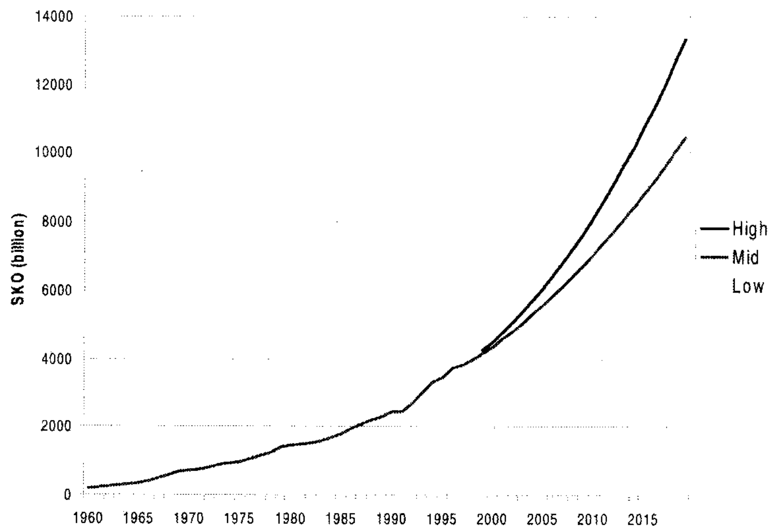


Figure 2 Aviation growth in terms of global SKO (seat kilometres offered) between 1960 and 2020 (source: DTI data, personal communication)



further than one might suspect. Local air quality was the original driver for the development of aircraft engine emissions regulations by the International Civil Aviation Organization (ICAO), first promulgated in 1981 (although earlier local rules to the USA were introduced by the US Environmental Protection Agency in 1973). However, one of the initial drivers of interest in aviation's atmospheric effects was concern in the late 1960s and early 1970s that emissions of nitrogen oxides (NO_x, where $NO_x = NO + NO_2$) from a (proposed) fleet of supersonic aircraft flying in the stratosphere would significantly deplete stratospheric ozone (O_3), resulting in increased exposure of harmful ultraviolet (UV) radiation at the Earth's surface.[2,3] The scientific research programmes that this concern initiated

[2] H. S. Johnston, *Science*, 1971, **173**, 517.
[3] P. J. Crutzen, *Ambio*, 1972, **1**, 41.

were of quite epic proportions and laid many of the modern foundations of our understanding of stratospheric chemistry and physics. A more detailed account of these research programmes, and their development, is given elsewhere.[4] In fact, the US research programme proceeded *after* the decision had been taken in the US not to build a supersonic transport (or 'SST') and was partly in response to the intentions of the UK and France to build Concorde, and the USSR the Tupolev TU-144. During this early work it was conjectured that the current subsonic fleet may, in fact, impact upon tropospheric O_3, following the proposal of Crutzen[5] that *in situ* production dominated tropospheric O_3.

Interest in the potential effects of subsonic aviation ensued in the 1980s and early 1990s.[6] 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 its chemistry. Initially, attention was focussed upon the effects of aircraft NO_x emissions on tropospheric O_3 production. Whereas O_3 in the mid to upper stratosphere 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 Earth's surface. More recently, other effects such as those of contrails (condensation trails) have been studied intensively, although studies of contrails and climate can be traced back to the early 1970s.[7]

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 (strictly, ice-supersaturation), contrails may be very short-lived or persistent, sometimes spreading by wind-shear, sedimentation and diffusion into cirrus-like clouds that are ultimately unrecognizable as having been caused by aircraft. Other effects on climate from associated particle emissions and the enhancement of cirrus clouds have also been suggested.

In 1996, the Intergovernmental Panel on Climate Change (IPCC), at the request of ICAO, announced its intention to assess aviation's effects on the global atmosphere; this was completed in 1999.[8] However, the IPCC was not the first assessment: other previous assessments and syntheses include, *e.g.* Schumann (1994),[9] Wahner *et al.* (1995),[10] Friedl *et al.* (1997),[11] Brasseur *et al.* (1998).[12] This

4 D. S. Lee, *Annex 1* to *QinetiQ report QINETIQ/FST/CR030440*, D. H. Lister and P. D. Norman (eds.), 2003.

5 P. J. Crutzen, *Tellus*, 1974, **26**, 47.

6 U. Schumann, *Air Traffic and the Environment*, Lecture Notes in Engineering, No. 60, ed. U. Schumann (ed.), Springer-Verlag, Berlin, 1990.

7 D. R. Lyzenga, PhD thesis, University of Michegan, Ann Arbor, 1973.

8 IPCC, *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, Cambridge, 1999.

9 U. Schumann, *Ann. Geophys.*, 1994, **12**, 365.

10 A. Wahner, M. A. Geller, F. Arnold, W. H. Brune, D. A. Cariolle, A. R. Douglass, C. Johnson, D. H. Lister, J. A. Pyle, R. Ramaroson, D. Rind, F. Rohrer, U. Schumann and A. M. Thompson, 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, 1995.

period saw tremendous activity originating from national/international research programmes and dedicated efforts for the IPCC report. Shortly before the completion of the IPCC assessment, Boeing announced that it no longer intended to pursue the development of an SST, largely on economic and environmental (noise) grounds. This, along with the overspending and overrunning NASA space station programme, precipitated the termination of NASA's Atmospheric Effects of Aviation Programme (AEAP). Subsequently, some activities were restarted in the US, albeit at a much lower budgetary level, primarily on global modelling and engine emissions. In Europe, however, the IPCC aviation report[8] provided a springboard from which several research programmes into atmospheric science and technology were initiated under the European Commission's Fifth Framework Programme and included: PARTEMIS, NEPAIR, TRADEOFF, INCA, AERO2K, SCENIC and CRYOPLANE.* The bulk of the efforts of these programmes were directed at subsonic effects/technology, with the exception of SCENIC and minor components of TRADEOFF, which addressed supersonic impacts.

In Section 2, the emissions from aircraft in terms of species and their global nature are described. Section 3 gives a brief description of the climate metric, radiative forcing, followed by specific aviation impact quantification (Section 4). In Section 5, some potential emissions reduction approaches are described and some brief conclusions drawn in Section 6.

2 Aircraft Emissions

Aircraft Engine Emissions

The civil subsonic fleet is dominated by aircraft equipped with turbofan gas turbine engines; the turboprop fleet being relatively small on a global scale. Gas turbine engines are technologically advanced systems that require stringent characteristics of safety and durability. Engine emissions are regulated through certification requirements of ICAO (ICAO, 1981;[13] most recent update ICAO, 1995[14]) for NO_x, unburned hydrocarbons (HCs), carbon monoxide (CO), and smoke. It is worth reinforcing what these regulations are: they are manufacturing standards, not an in-service compliance regime. Thus, measurements are made using carefully prescribed methodologies on a limited number of engines for certification purposes.

In recent years, significant improvements in fuel efficiency have been achieved

* See *e.g.*, http://www.ozone-sec.ch.cam.ac.uk/clusters/Corsaire_Website/corsaire_index.htm

[11] R. R. Friedl, S. L. Baughcum, B. Anderson, J. Hallett, K.-N. Liou, P. Rasch, D. Rind, K. Sassen, H. Singh, L. Williams and D. Wuebbles, *Atmospheric Effects of Subsonic Aircraft: Interim Assessment of the Advanced Subsonic Assessment Program*, NASA Reference Publication 1400, Washington D.C., 1997.

[12] G. P. Brasseur, R. A. Cox, D. Hauglustaine, I. Isaksen, J. Lelieveld, D. H. Lister, R. Sausen, U. Schumann, A. Wahner and P. Wiesen, *Atmos. Environ.*, 1998, **32**, 2329.

[13] ICAO, *International Standards and Recommended Practices, Environmental Protection, Annex 16 to the Convention on International Civil Aviation, Vol. II, Aircraft Engine Emissions*, (1st edn.), International Civil Aviation Organization, Montreal, 1981.

[14] ICAO, *ICAO Engine Exhaust Emissions Databank*, 1st Edn., ICAO Doc. 9646-AN/943, International Civil Aviation Organization, Montreal, 1995.

to reduce operating costs. Also, emissions of some pollutants, particularly smoke, have been reduced. Emissions of CO_2 and H_2O scale with fuel consumption depending on the specific fuel carbon to hydrogen ratio. Emissions of NO_x and soot are highest at high power settings whilst CO and HCs are highest at low power settings as they are the result of incomplete combustion. In general, emissions of NO_x, 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 are described briefly below. For a more detailed account, the reader is referred to other reviews.[8,12]

Oxides of Nitrogen (NO_x). 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 content of the fuel. Its production is a complex function of combustion temperature, pressure and combustor design. Although NO_x emissions can be reduced, as overall engine pressure ratios have increased (to reduce fuel consumption), this has implied higher temperatures and pressures in the combustor, which tend to increase NO_x production. Hence, to address NO_x emissions, different combustor technologies have been developed.[8] 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. However, NO is quickly converted into NO_2 in the atmosphere.

Particles. Particles emitted from aircraft can be categorized into volatile and non-volatile components; this being partially an operational measurement definition. Non-volatile particles primarily include carbonaceous material formed in the primary combustion zone arising from incomplete combustion of the fuel. A fleet average emission index (EI) for soot of 0.04 g per kg fuel burned has been estimated[15] with a large uncertainty (at best a factor of 2). These soot particles are thought to have only a minor direct impact upon climate (see the Section on Sulfate and Soot Particles). However, soot and other particles emitted from aircraft engines play a role in contrail and cirrus cloud enhancement, as shown later. Soot particles *per se* are not regulated but rather the so-called 'Smoke Number',[13,14] which is an optical measurement of, effectively, the larger soot particles.

Volatile particles are primarily composed of sulfate, although recent research suggests that some smaller fraction of these particles is composed of organic material.[16] Most of the sulfur in the fuel is expected to be emitted as sulfur dioxide (SO_2).[17] However, some oxidation through to S^{VI} (*e.g.* SO_3, H_2SO_4) is possible within the engine itself.[18] The fraction of total gaseous sulfur in the engine exit plane is estimated to be up to 5% S^{VI}: however, this estimate is highly

[15] A. Döpelheuer, SAE Paper No. 2001-01-3008, Proceedings of the 2001 Aerospace Congress, September 10–14, 2001.
[16] B. Kärcher, *Atmos. Res.*, 1998, **46**, 293.
[17] R. C. Miake-Lye, M. Martinez-Sanchez, R. C. Brown and C. E. Kolb, *J. Aircraft*, 1993, **30**, 467.
[18] S. P. Lukachko, I. A. Waitz, R. C. Miake-Lye, R. C. Brown and M. R. Anderson, *J. Geophys. Res.*, 1998, **103**, 16159.

Table 1 Fuel, CO_2, NO_x and $EINO_x$ for 1991/92, 1999, 2000, 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[32]
TRADEOFF 2000				13.8	TRADEOFF (2003)[46]
ANCAT/EC2 – 2015	286.9	247	3.53	12.3	Gardner *et al.*, 1998[32]
NASA 1992				12.6	Baughcum *et al.*, 1996[34]
NASA 1999				13.2	Sutkus *et al.*, 2001[35]
NASA – 2015				13.7	Baughcum *et al.*, 1998[37]
FESG Fa1 – 2050	471.0	405	7.2	15.2	FESG, 1998[38]
FESG Fa2 – 2050	487.6	419	5.5	11.4	FESG, 1998[38]
FESG Fc1 – 2050	268.2	231	4.0	15.0	FESG, 1998[38]
FESG Fc2 – 2050	277.2	238	3.1	11.3	FESG, 1998[38]
FESG Fe1 – 2050	744.3	640	11.4	15.3	FESG, 1998[38]
FESG Fe2 – 2050	772.1	664	8.8	11.4	FESG, 1998[38]

uncertain. Emission of S species is thought to be important for volatile particle formation from sulfuric acid (H_2SO_4) and gas-phase H_2SO_4 has now been detected in the wake of aircraft.[19]

Measurements of particle emissions from aircraft, engines and combustors have shown that they lie in the 3 nm to 4 μm aerodynamic diameter size range. The soot aerosol size distribution at the engine exit is log–normal, with number concentrations peaking in the 40–60 nm size range. Emission indices fall within the range of 10^{12} soot aerosol particles per kg fuel for current advanced combustors and up to 10^{15} for older engines.[20]

Other Trace Species. Other trace species have not been as well characterized as, for example, NO_x. Hydroxyl radicals (OH) are produced as a part of the combustion process and control the oxidation of NO_x and S species to their oxidized forms. Few measurements of OH have been made, despite its importance.[21] Tremmel *et al.* (1998)[22] used measurements of other odd N species in the plume to infer OH concentrations of 1 ppmv or less. However, recent static measurements using Laser Induced Fluorescence (LIF) indicated concentrations of 100 ppbv or less.[23] Recent measurements from the PARTEMIS study indicate much lower OH concentrations, of the order 1 ppb.[24] Clearly, given the importance of OH,

[19] J. Curtuis, B. Sierau, F. Arnold, R. Baumann, R. Busen, P. Schulte and U. Schumann, *Geophys. Res. Lett.*, 1998, **25**, 923.

[20] A. Petzold, A. Döpelheuer, C. A. Brock and F. P. Schröder, *J. Geophys. Res.*, 1999, **104**, 22171.

[21] T. F. Hanisco, P. O. Wennberg, R. C. Cohen, J. G. Anderson, D. W. Fahey, E. R. Keim, R. S. Gao, R. C. Wamsley, S. G., Donnelly, L. A. DelNegro, R. J. Salawitch, K. K. Kelly and M. H. Proffitt, *Geophys. Res. Lett.*, 1997, **24**, 65.

[22] H. G. Tremmel, H. Schlager, P. Konopka, P. Schulte, F. Arnold, M. Klemm and B. Droste-Franke, *J. Geophys. Res.*,1998, **103**, 10803.

[23] S. Bockle, S. Einecke, F. Hildenbrand, C. Orlemann, C. Schulz, J. Wolfrum and V. Sick, *Geophys. Res. Lett.*, 1999, **26**, 1849.

[24] C. W. Wilson, A. Petzold, S. Nyeki, U. Schumann and R. Zellner, *Aerosp. Sci. Technol.*, 2004, **8**(2), 131.