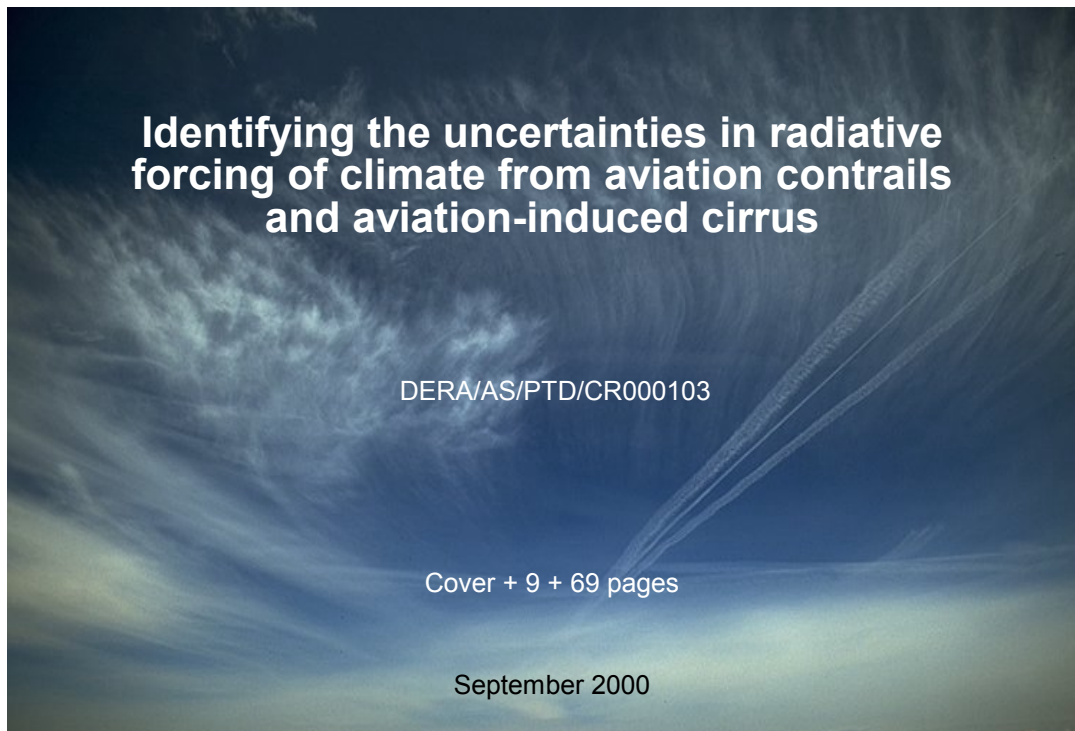


UNCLASSIFIED



D. S. Lee¹, P. E. Clare¹, J. Haywood², B. Kärcher³, R. W. Lunn², I. Pilling¹, A. Slingo⁴ and J. R. Tilston¹

¹Defence Evaluation and Research Agency, Farnborough, Hampshire GU14 0LS, United Kingdom;

²Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, United Kingdom

³Deutsche Forschungsanstalt für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Wessling, Germany;

⁴Hadley Centre for Climate Research and Prediction, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, United Kingdom

DERA

DERA is an Agency of the UK Ministry of Defence

UNCLASSIFIED

UNCLASSIFIED

| Customer Information | |
|---------------------------|---|
| Customer Reference Number | PO23474 |
| Project Title | The effects of aviation contrails on global climate |
| Company Name | Department of Environment Transport and the Regions |
| Customer Contact | Drs C. Johnson & G. McFadyen |
| Contract Number | EPG 1/1/95 |
| Milestone Number | 2 of 2 |

This Document was produced by DERA for The Department of Environment Transport and the Regions Under Order/Contract reference EPG 1/1/95

© Crown copyright 2000 Defence Evaluation and Research Agency UK


Approval for wider use of releases must be sought from:

Intellectual Property Department, Defence Evaluation and Research Agency,
DERA Farnborough, Farnborough, Hampshire GU14 0LX

UNCLASSIFIED

Authorisation

Prepared by D. S. Lee
Title Technical Team Leader, Atmospheric Processes

Signature 
Date 17-09-2000
Location DERA Pyestock

Approved by C. W. Wilson
Title Technical Area Leader, Combustion and Environment

Signature 
Date 22 Sept 2000

Authorised by R. Onions
Title Business Area Manager, Propulsion and Performance Department

Signature 
Date 28/09/00

Record of changes

| Issue | Date | Detail of Changes |
|-------|----------------|-----------------------------|
| 1.0 | September 2000 | Final report issued to DETR |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

Executive summary

This report is a final report to the DETR on evaluating the effects of aviation contrails on global climate for Global Atmosphere Division (contract EPG 1/1/95). DERA have co-ordinated and provided input to this project along with The Hadley Centre for Climate Prediction and Research, the Meteorological Office and the Deutsches Zentrum für Luft und Raumfahrt (Institute of Atmospheric Physics).

The three key requirements of DETR were identified as:

1. **a review of the main causes of uncertainty** in the climate effect of contrails;
2. a review of **options for reducing contrails**;
3. and a **synthesis of these reviews** to produce a prioritised set of potential research projects.

Requirement 1, a review of the main causes of uncertainties has been tackled by formulating ten key questions relating to uncertainties, which are answered in the report. In order to reduce the uncertainties in radiative forcing associated with *contrails* and *cirrus clouds* (aviation-induced cirrus formation) that were represented by radiative forcing estimates given recently by the Intergovernmental Panel on Climate Change, we have concluded the following:

Reducing the uncertainties in estimates of radiative forcing from persistent contrails

- The relative roles of sulphur, organic compounds and chemi-ions in particle production in the plume are not well understood. Moreover, the particle production in the engine itself is even more poorly understood: this represents a constraint for any improvement in knowledge of plume processes.
- The relative roles of homogeneous and heterogeneous freezing of particles are not well understood.
- The ways in which contrail-cirrus and natural cirrus clouds differ from each other in terms of radiative properties is not well understood.
- Only one in-flight demonstration of the effect of older vs newer engine technology on contrail initiation has been performed.
- The quantification of global and regional contrail coverage from observations is very poor.
- Databases and approaches to modelling contrail coverage should be improved. Specifically: air traffic movements, measurements of contrail coverage (see above), optical thicknesses, meteorological input data, quantification of future propulsive efficiencies. The validation of such approaches should be made, including direct measurements of radiation balance anomalies in a heavily trafficked area.
- Climate modelling of contrails should be progressed by incorporating improvements from the above into carefully-designed GCM experiments. It is necessary to understand the climate response, not merely radiative forcing estimates on regional and global scales.

Reducing the uncertainties in estimates of radiative forcing from aviation-induced cirrus

- There is very poor evidence for a causal link between increases in air traffic and increased cirrus coverage.
- A better quantification of the optical thickness of contrail–cirrus transitions should be made.
- The potential coverage of contrail-induced cirrus and its radiative properties are unknown.
- Whether residual particles from short-lived contrails are better cloud condensation nuclei than background particles is unknown.
- Databases and approaches to estimating aviation-induced cirrus coverage should be improved.

In terms of **requirement 2, options to reduce contrails**, operational issues and technological issues have been considered. Operational possibilities exist through advanced flight planning and air traffic management but we have concluded that the state of the science on understanding contrail quantification and impacts is too poor at present to actively pursue operational measures to reduce contrails. On technology, we conclude that there are no current measures that can reduce contrails.

UNCLASSIFIED

For **requirement 3**, a **synthesis of these reviews** to produce a prioritised set of potential research projects, we have concluded that two approaches are possible. One is to quantify the direct relationship between satellite measurements of radiation balance parameters and aircraft movement data. The other is to improve our knowledge of all the processes that link the presence of an aircraft to the occurrence of a radiation balance anomaly. The first approach would give rise to information on the current relationship but little capability for predicting how that relationship might change in the future. The second approach would lead to greatly increased understanding of the current uncertainties and a strengthening of the weakest links in this long calculation chain.

The first approach, which potentially relies heavily on the availability of data from the Geostationary Earth Radiation Budget (GERB) instrument of the METEOSAT Second Generation satellite (MSG) to be launched in 2002), would be to measure the radiation balance anomaly associated with contrails in conjunction with air traffic control data. This would reduce the uncertainty in the effects of contrails on the radiation balance. In addition, using such data, the accuracy in forecasts of contrails, particularly those contrails that have greatest effect on the radiation balance, could be measured. This would improve techniques for forecasting contrails.

The second approach requires 8 steps as follows:

1. further measurements of contrail coverage from different regions of the globe;
2. quantitative evidence of the formation of cirrus cloud from aircraft exhaust particles;
3. a better understanding of particle formation including the engine and in the plume;
4. observations quantifying the differences between 'clean' and aviation-impacted cirrus;
5. an improved aircraft movement database for contrail coverage calculations;
6. a better quantification of the connection between cirrus coverage trends and air traffic;
7. more data on the impact of engine/airframe efficiency on contrail formation;
8. incorporation of RF calculations into a GCM framework.

These requirements have been distilled out from the conclusions of the review of uncertainties (requirement 2) so that all the above 8 elements are considered necessary to reduce the uncertainties in radiative forcing from contrails and aviation-induced cirrus. Any future research project to address such uncertainties would need to consider the above 8 elements, some of which will be contributed to by new or planned projects within Europe (2, 4 and 5).

However, there is to our knowledge, no single project in place, either at the national or international level, that specifically aims to reduce the overall uncertainties by addressing these disparate areas to provide new radiative forcing estimates.

An integrated programme looking at the range of requirements outlined above and exploiting other research both past and present is *the* research requirement.

List of contents

| | |
|---|-----------|
| Authorisation | 1 |
| Record of changes | 2 |
| Executive summary | 3 |
| 1 Introduction | 9 |
| 1.1 Background to this report | 9 |
| 2 Contrails, aviation and climate | 11 |
| 2.1 Contrails and climate | 11 |
| 2.2 Contrail formation—aircraft wake and plume interactions | 13 |
| 2.3 Contrail formation—thermodynamics and prediction | 13 |
| 2.4 Contrail formation—particle precursors | 15 |
| 3 Identifying the uncertainties | 19 |
| 3.1 “What are the uncertainties in mechanisms of contrail formation?” | 19 |
| 3.2 “How much is known about cirrus cloud resulting from aircraft emissions, as opposed to ‘young’ persistent contrails?” | 26 |
| 3.3 “How do changes in aircraft engine technology affect contrail formation?” | 31 |
| 3.4 “Is the quantification of contrail coverage adequate?” | 33 |
| 3.5 “Are trends in global cirrus cloud coverage connected with trends in air traffic?” | 36 |
| 3.6 “Are the approaches and global databases for estimating radiative forcing adequate?” | 39 |
| 3.7 “Is it possible to determine radiative forcing from measurements of radiation balance anomalies?” | 43 |
| 3.8 “How good is the representation of contrails/cirrus for estimating radiative forcing and subsequent climate change?” | 47 |
| 3.9 “What potential is offered by operational measures for reducing contrails?” | 51 |
| 3.10 “What potential is offered by technological measures for reducing contrails?” | 53 |
| 4 Conclusions | 55 |
| 4.1 Reducing the uncertainties in estimates of radiative forcing from contrails | 55 |
| 4.2 Reducing the uncertainties in estimates of radiative forcing from aviation-induced cirrus | 56 |
| 5 Reducing the uncertainties—research priorities | 57 |
| 5.1 Current complimentary work | 57 |
| 5.2 Research priorities | 58 |
| 6 References | 61 |
| A Sensitivity of AVHRR, SEVIRI and GERB to contrails and cirrus | 67 |
| Distribution list | 69 |
| Report documentation page | 71 |

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

List of Figures

- Figure 2-1 Estimates of globally and annually averaged radiative forcing ($W m^{-2}$) arising from various effects of 1992 aviation on the atmosphere. For a detailed explanation, see source: IPCC SPM (1999), Figure 2. 12
- Figure 2-2. Diagonal curves represent the approximate critical pressure altitudes where contrails form at a given ambient temperature, parameterised by the ambient saturation ratio S_a (S_a is equal to the relative humidity RH divided by 100%). Subsonic and supersonic flight levels are indicated. 14
- Figure 2-3 Schematic diagram of the H_2O saturation vapour pressures over liquid water (solid curve) and over ice (dashed curve) versus temperature. Line AB illustrates how an air parcel mixes isobarically in a jet plume, assuming that heat and water vapour mix similarly. A contrail forms after crossing the saturation curve and age increases from A to B. The line tangent to the liquid saturation curve is used to derive the formation threshold temperatures, which lie between $T+$ (water saturated air) and $T-$ (dry air). Figure courtesy of Klaus Gierens, with changes. 15
- Figure 2-4 Schemata of aerosol dynamics and related chemistry in aircraft exhaust plumes and contrails. Round and rectangular boxes denote species emitted and formed in situ, respectively. The arrows and corresponding labels indicate transformation processes that are described by current numerical simulation models. 16
- Figure 2-5 Size distributions of the particle types present in aircraft exhaust plumes. If a contrail forms, these spectra change (not shown) and ice particles are created (red curve). Bars denote variabilities of the respective parameters (Kärcher, 1999). 16
- Figure 2-6 Exhaust particles from the plume of an F-16 aircraft in flight. Photomicrograph taken with a transmission electron microscope. Figure by P. Sheridan downloaded from the web site: www.cmdl.noaa.gov/aerosol/about/sheridan/particles.html. 18
- Figure 3-1 Ice particle size distribution and associated measurement uncertainties in a nascent contrail observed with an optical spectrometer in the plume of a B737 burning low sulphur fuel (2 ppm by mass). Data courtesy of Franz Schröder, adapted from Schröder et al. (2000a). 21
- Figure 3-2 Soot-induced freezing (heterogeneous) pathway leading to contrails (Kärcher, 1998a). Soot particles acquire a (partial) liquid H_2SO_4/H_2O coating due to adsorption of oxidised sulphur gases and scavenging of volatile droplets. They also trigger freezing if the fuel S content is very low (a few ppm by mass), suggesting an additional sulphur-free heterogeneous freezing mode (dashed arrow). Few ice particles may also nucleate without water activation (dot-dashed arrow). Soot dominates ice formation at and slightly below threshold formation temperatures. Homogeneous freezing may also occur and enhance the ice mass for lower temperatures and/or higher fuel S contents (not shown). Ice crystal shapes are close to spherical in young contrails, but may vary in ageing contrails as indicated by the hexagon. Soot cores may reside inside the crystals, or are attached at their surface. 22
- Figure 3-3 Simulated size distributions of acid (solid curve) and mixed soot/sulphate particles (dashed curve) in an evaporating short-lived contrail in a high sulphur plume at about 20 s plume age. Numbers denote distinct modes in the particle spectra, caused by coagulation processes between these particles and the contrail ice crystals. Data courtesy of Fangqun Yu, adapted from Yu and Turco (1998). 24
- Figure 3-4 Representative selection of observed size-resolved particle concentrations illustrating the transition of contrails into young upper tropospheric cirrus clouds. S: exhaust soot spectrum in a plume without contrail. A: Evaporating, short-lived contrail. Cf: Young cirrus cloud. Others: Persistent contrails at different plume ages. Figure taken from Schröder et al. (2000b). 27
- Figure 3-5 Transformation of a contrail into a cirrus cloud. Two-dimensional large-eddy simulation using observed wind and temperature profiles, assuming moderate ice supersaturations. Vertical axis: altitude (in m), horizontal axis: contrail width (in m), contour lines: ice water content (in mg/m^3). Figure courtesy of Klaus Gierens, adapted from Gierens and Jensen (1998). 28
- Figure 3-6 Evolution of contrail–cirrus formation from satellite imagery arising from NASA DC8 flight track (Minnis et al., 1998). 34
- Figure 3-7 Shortwave (SW), longwave (LW) and net instantaneous radiative flux change from contrails with 100% cover under mid-latitude summer conditions averaged over a day as a function of optical depth ($0.55 \mu m$): near the top of the atmosphere (50 km) and surface (0 km). From Meerkötter et al. (1999). 37

UNCLASSIFIED

Figure 3-8 Persistent contrail coverage for 1992 (upper panel) from Sausen et al. (1998) and 2050 under Fa1 scenario (lower panel) from Gierens et al. (1999) 40

Figure 3-9 Global distribution of radiative forcing from contrails at the top of the atmosphere from 1992 and 2050 aircraft (Minnis et al., 1999). 49

1 Introduction

1.1 Background to this report

1.1.1 This is the Final Report for '*The effects of aviation contrails on global climate*' for the Department of the Environment, Transport and the Regions (contract EPG 1/1/95). The project involved DERA, the Hadley Centre for Climate Prediction and Research, the Meteorological Office and DLR, Oberpfaffenhofen (Institute for Atmospheric Physics).

1.1.2 The DETR identified three key requirements for this work:

1. a review of the main causes of uncertainty in the climate effect of contrails;
2. a review of options for reducing contrails;
3. and a synthesis of these reviews to produce a prioritised set of potential research projects.

In DERA's bid and subsequent contract documentation a number of particular questions were identified:

- Q1. What are the uncertainties in mechanisms of contrail formation?
- Q2. How much is known about cirrus cloud resulting from aircraft emissions, as opposed to 'young' persistent contrails?
- Q3. Is the quantification of contrail coverage good enough?
- Q4. Are trends in global cirrus cloud coverage connected with trends in air traffic?
- Q5. How reliably can we link the flights of individual aircraft with radiative balance anomalies using satellite observations?
- Q6. How do properties of aircraft engines' exhaust emissions affect contrail formation?
- Q7. Are the global databases and approaches for estimating radiative forcing adequate?
- Q8. How good are current climate modelling techniques and representation of contrails/cirrus for estimating radiative forcing and subsequent climate change?
- Q9. What potential is offered by operational measures for reducing contrails?
- Q10. What potential is offered by technological measures for reducing contrails?

1.1.3 In this report, the above questions are dealt with in turn for clarity and brevity.

1.1.4 Four meetings have been held in relation to the work.

1. A first start-up meeting at DERA Farnborough attended by D. S. Lee (DERA Propulsion Department), J. R. Tilston (DERA Propulsion Department), R. W. Lunnon (Met. Office), G. McFadyen (DETR), P. Clare (DERA Space Department) and B. Kärcher (DLR).
2. A second meeting on climate modelling issues was held at the Hadley Centre that was attended by G. J. Jenkins (Hadley Centre), J. Haywood (Met. Office Research Flight), A. S. Slingo (Hadley Centre), D. S. Lee and R. W. Lunnon,
3. A third meeting was held at DLR Oberpfaffenhofen between D. S. Lee and B. Kärcher with Ulrich Schumann, also consulted were: Robert Sausen, Franz Schröder, Andreas Petzold, Peter Wendling and Klaus Gierens (DLR).
4. A fourth meeting was held at the Hadley Centre for Climate Prediction and Research between D. S. Lee, G. J. Jenkins, A. Slingo and J. Haywood to finalise the sections of the report related to calculations of radiative forcing.

1.1.5 All meetings were extremely useful and generated more detail to the questions identified in the proposal. However, it was noteworthy that further questions were not identified and that the feeling was that the main issues had indeed been identified in the questions posed above.

UNCLASSIFIED

- 1.1.6 Throughout this report, the recent report of the Intergovernmental Panel on Climate Change (IPCC)—*Aviation and the Global Atmosphere*—is extensively referred to by Chapter.

2 Contrails, aviation and climate

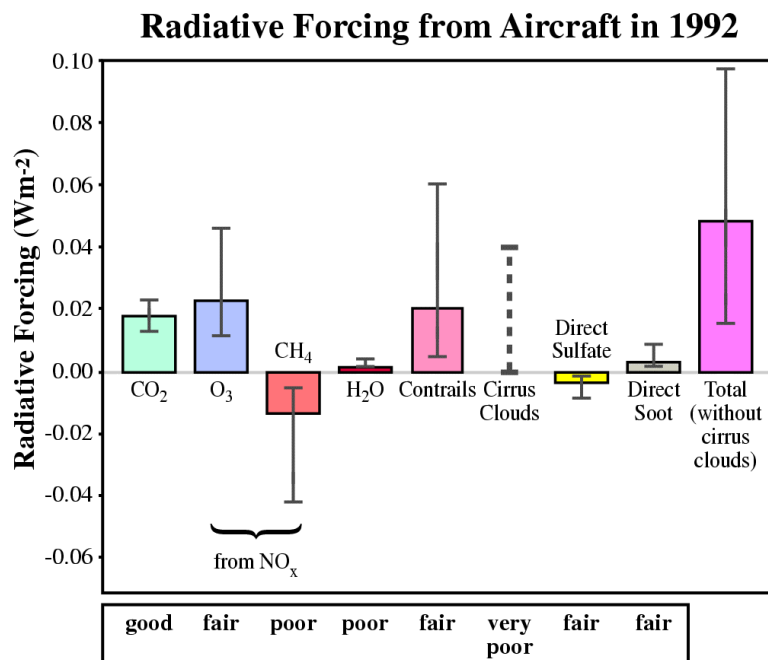
Summary

- Contrails arise from the water emitted in the exhaust of aircraft engines burning kerosene at high altitudes, which condenses on particles arising from the combustion process. Their presence or absence is largely a function of the ambient temperature and relative humidity.
- The thermodynamic criterion for prediction of contrails as a function of a few atmospheric and engine-related parameters is well established and has been verified by *in situ* observations. This approach does not require a detailed knowledge of microphysics of ice crystal formation. These parameters must be known with sufficient accuracy, which may be a problem in the case of atmospheric relative humidity. However, there are no basic uncertainties associated with the prediction of contrails from such parameters.
- Much work has been committed to researching the effects of contrails on climate since 1990, culminating in the IPCC Special Report in 1999 as a definitive statement of current knowledge.

2.1 Contrails and climate

- 2.1.1 The idea that contrails can affect climate is not new: potential climate effects of contrails were discussed between the late 1960s and the early 1980s (e.g. Appleman, 1966; Cannon, 1971; Lyzenga, 1972, 1973; Chagnon, 1981). However, these studies of contrails did not receive much attention.
- 2.1.2 The broader potential adverse effects of aircraft emissions were studied in the 1970s when the development of a fleet of supersonic aircraft was proposed. However, contrails were not the principle issue but rather the effect of NO_x emissions on stratospheric ozone depletion. The scientific landmarks of the time were papers by Crutzen (1971) and Johnston (1971) who postulated significant stratospheric ozone depletion from supersonic aircraft NO_x emissions. In the event, only a limited fleet was developed by the United Kingdom and France in the form of Concorde. The only other civil supersonic aircraft is the Tupulov 144, which only saw 1 year's active civilian transport service after a chequered history of two catastrophic crashes: one at the Paris airshow in 1973 and another in Russia in 1978.
- 2.1.3 Renewed interest ensued in the late 1980s and early 1990s on the potential effects of subsonic aircraft, this time on climate (Schumann, 1990). The effects of subsonic aviation on tropospheric ozone had been discussed earlier by Hidalgo and Crutzen (1977) and Derwent (1982). The potential effect of contrails was highlighted by a number of authors at an international colloquium held in Germany in 1990 (Schumann, 1990). Since then, research into the potential effects of contrails on climate has continued, culminating in extensive research in the late 1990s under research programmes such as, for example, CHEMICON (EU), Schadstoffe in der Luftfahrt (Germany) and SASS (NASA, US). Knowledge was recently synthesised in the Special Report of the Intergovernmental Panel on Climate Change—*Aviation and the Global Atmosphere* (IPCC, 1999).
- 2.1.4 The IPCC report was a landmark in the discussion of the effects of aviation on the global atmosphere and estimates of radiative forcing (hereafter referred to as RF) of climate from various aircraft emissions and their effects were made. Figure 2-1 over, adapted from the IPCC Summary for Policymakers (IPCC SPM, 1999), shows the large uncertainties associated with contrail and cirrus effects (the two being linked). The vertical axis shows global average radiative forcing in watts per square metre, the bars show the best estimate of radiative forcing whilst the whiskers show the uncertainty range. The descriptors below indicate an assessment of the quality of the estimate based upon current knowledge. As is quite clear from Figure 2-1, the contrail and cirrus effects are quite large and rather uncertain.

Figure 2-1 Estimates of globally and annually averaged radiative forcing ($W m^{-2}$) arising from various effects of 1992 aviation on the atmosphere. For a detailed explanation, see source: IPCC SPM (1999), Figure 2.



- 2.1.5 Whilst the IPCC concluded that present day effects of aviation from all forcings are relatively small compared to other sources (3.5% of 1992 levels), it is the rapid growth of aviation that gives rise to concern. The scenarios used by the IPCC for 2050 utilised average projected traffic growth rates (1990–2050) ranging between 2.2% and 4.7% per year. Under the scenario Fa1¹, the total fossil fuel consumption by aviation is projected to be 3% (compared to 2.4% in 1992) but the contribution to total RF, 5%.
- 2.1.6 That one particular source sector should have such a potentially significant effect on future climate is quite remarkable. The rapid historical growth and projected growth rates are discussed extensively in the IPCC report and are not discussed here further.
- 2.1.7 The prime motivation for this present work arises from the relative sizes of the potential RF from contrails and cirrus cloud and their associated uncertainties shown in Figure 2-1. The question underlying this report is: 'how can the uncertainties associated with the radiative forcing (RF) from aviation contrails and potential increases in cirrus coverage induced by aircraft emissions be reduced'?
- 2.1.8 In this Section (2), a brief overview is given of the processes involved in contrail formation. In Section 3, questions are posed which have been formulated around uncertainties identified in a preliminary assessment. In Section 4, the main conclusions are given and the research priorities for reducing the uncertainties given in Section 5.

¹ Fa1 denotes EESG (ICAO Forecasting and Economic Support Group) IS92a GDP assumptions, technology scenario 1. See Chapter 9 of IPCC for a detailed explanation and discussion of the scenarios.

2.2 Contrail formation—aircraft wake and plume interactions

- 2.2.1 Before considering contrail formation in terms of thermodynamics and microphysics, some basic properties of the aircraft, its wake and the plume are considered.
- 2.2.2 A detailed treatment of plume dynamics and the aircraft wake is not necessary for the purposes of this work, merely the basic principles. The wake vortices emanate from the wing tips and trap the jet exhaust. The vortices rotate and can last for 10–100 s. The period after that is characterised by turbulent dispersion. The vortices can then be observed (if contrails form) to form a primary and secondary wake, where the primary wake is the downward travelling vortex pair (for two or four engined aircraft) and the secondary wake is a less well ordered 'curtain' of material above the trailing vortices (Sussmann and Gierens, 1999).

2.3 Contrail formation—thermodynamics and prediction

- 2.3.1 Contrails are the most obvious indication of the presence of air traffic. Even the casual observer will notice that sometimes a contrail is very short-lived, sometimes persistent or even completely absent. Combustion of aviation fuel (kerosene) results in the release of water vapour that rapidly condenses on particles and freezes at the low temperatures prevalent in the upper troposphere and lower stratosphere. If the relative humidity of the atmosphere is high (or more strictly speaking, supersaturated with respect to ice), then the contrails may be long lasting: if it is low, the contrail will rapidly evaporate into the drier ambient air. When contrails are long lasting, or persistent, they may grow by diffusion and wind-shear and, in some cases when many contrails are present, they can spread out to form a cirrus coverage that cannot be distinguished from natural cirrus. Persistent contrails are well known by amateur and professional weather observers and meteorologists to be a good indication of an approaching frontal system.
- 2.3.2 From the above description, three basic parameters control contrail formation: water released from combustion, ambient temperature and relative humidity. The water released is a simple function of the amount of fuel burned at cruise altitudes. However, the design of the engine may result in varying temperatures of the exhaust gases between engines (principally older ones and more modern engines) and this will dictate whether a contrail is triggered or not for the same ambient temperature and humidity. Nonetheless, it is apparent that temperature and relative humidity are the principal determinants of whether a contrail is formed, and its persistence.
- 2.3.3 That there is a dependence on relative humidity and temperature has long been recognised. Schmidt (1941) and Appleman (1953) described the basic theory of contrail formation. The history of contrail research and more recent developments has been given by Schumann (1996) in an erudite review.
- 2.3.4 The basic thermodynamic principles are now considered. Such a thermodynamic approach does not require dynamical and microphysical details of contrail formation to be known. We briefly summarise how the threshold conditions – the atmospheric temperatures (T), pressures (p) and relative humidities (RH) at which contrails form – are derived. These conditions are summarised in Figure 2-2, together with the flight levels of subsonic and supersonic aircraft.

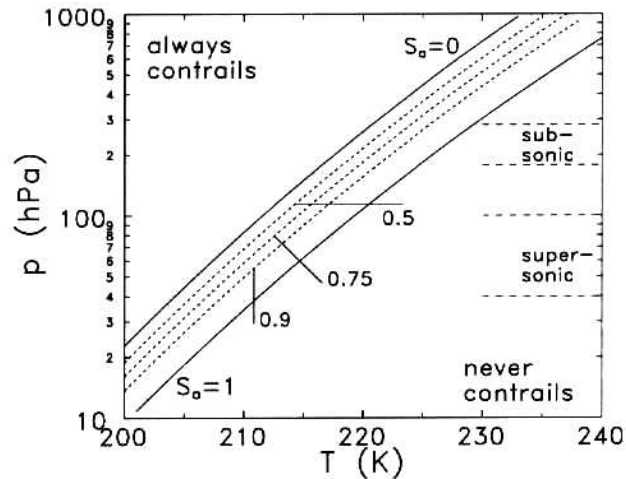


Figure 2-2. Diagonal curves represent the approximate critical pressure altitudes where contrails form at a given ambient temperature, parameterised by the ambient saturation ratio S_a (S_a is equal to the relative humidity RH divided by 100%). Subsonic and supersonic flight levels are indicated.

- 2.3.5 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. A contrail will form when saturation with respect to liquid water is reached or surpassed in the plume.
- 2.3.6 The thermodynamic relationship for contrail formation requires knowledge of the air pressure, temperature, and relative humidity at a given flight level. Also required are the fuel properties such as the emission index of H_2O , the combustion heat, and the overall aircraft propulsion efficiency. The thermodynamic criterion linking these parameters is well established and has been verified by *in situ* observations.
- 2.3.7 The thermodynamic relationship for contrail formation is derived with the help of Figure 2-3. The saturation vapour pressure curves separate saturated (contrail-forming) from unsaturated (contrail-dissipating) regions. An air parcel starting at the exit plane of a jet engine (characterised by temperatures and water vapour concentrations well outside the graph) may pass point A of the mixing line during cooling and mixing. Typically, this happens within a few tenths of a second after the exhaust exited the engines. The parcel then crosses the *liquid* saturation curve (solid line), where a contrail forms. The state of the atmosphere is represented by the point B, where the mixing line ends some time after emission (point B is reached asymptotically, provided the state of the atmosphere remains unchanged). If the atmosphere at B is (super-)saturated with respect to ice, a persistent contrail may develop, otherwise the contrail starts evaporating when the mixing line again crosses the *ice* saturation curve.

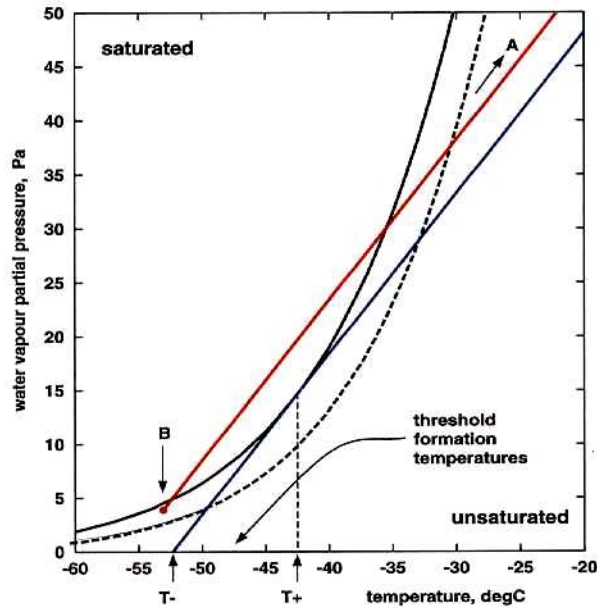


Figure 2-3 Schematic diagram of the H_2O saturation vapour pressures over liquid water (solid curve) and over ice (dashed curve) versus temperature. Line AB illustrates how an air parcel mixes isobarically in a jet plume, assuming that heat and water vapour mix similarly. A contrail forms after crossing the saturation curve and age increases from A to B. The line tangent to the liquid saturation curve is used to derive the formation threshold temperatures, which lie between $T+$ (water saturated air) and $T-$ (dry air). Figure courtesy of Klaus Gierens, with changes.

2.4 Contrail formation—particle precursors

- 2.4.1 Particles on which water vapour condenses originate from background aerosol taken into the engine air intake, are produced within the engine combustor, or are formed within the fresh exhaust plumes under cruise conditions. However, the particle number density from the background atmosphere are several orders of magnitude lower than that produced within the engine itself. Contrail ice particles predominantly form on these particles, although ambient aerosols entrained into the plume may in some cases also contribute to the particle budget in contrails.
- 2.4.2 The following aerosol types have been identified from *in situ* observations in aircraft exhaust plumes.
- Liquid aerosols that consist of sulphuric acid (H_2SO_4), H_2O , and condensable organic species resulting from homogeneous nucleation.** A fraction of these aerosols originates from chemi-ions (these are electrically charged molecular clusters produced within the engine combustor).
 - Non-volatile combustion aerosols that are mainly composed of black carbon soot and, to a much lesser extent, metallic particles.** The soot particles very likely acquire a liquid surface coating in the jet plume by interaction with sulphur (S) gases and H_2SO_4/H_2O droplets.
 - Ice particles formed via freezing nucleation in contrails that rapidly take up the emitted H_2O in an initial growth stage.** Figure 2-4 is a schematic representation of the physico-chemical processes that take place in aircraft plumes, involving these particle types (Kärcher, 1998a).

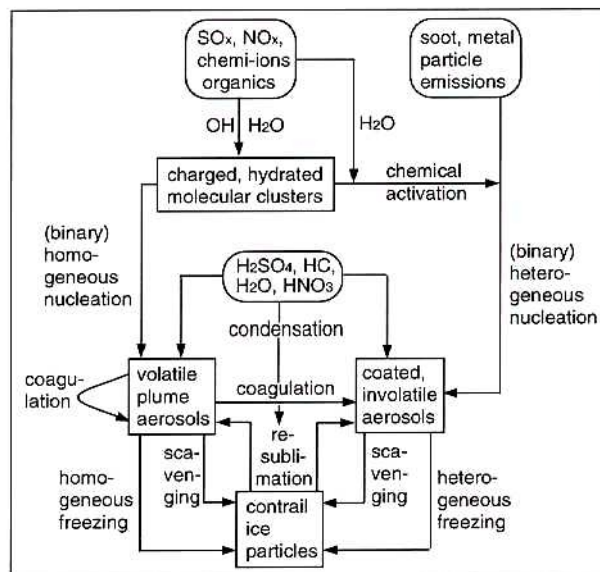


Figure 2-4 Schemata of aerosol dynamics and related chemistry in aircraft exhaust plumes and contrails. Round and rectangular boxes denote species emitted and formed in situ, respectively. The arrows and corresponding labels indicate transformation processes that are described by current numerical simulation models.

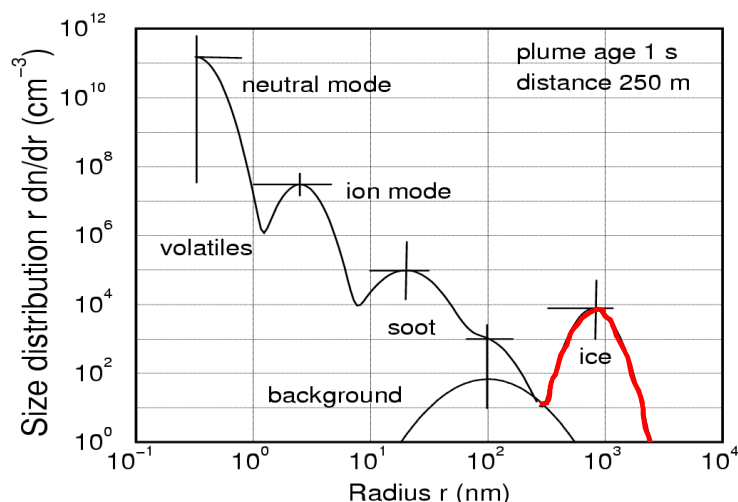


Figure 2-5 Size distributions of the particle types present in aircraft exhaust plumes. If a contrail forms, these spectra change (not shown) and ice particles are created (red curve). Bars denote variabilities of the respective parameters (Kärcher, 1999).

- 2.4.3 In the following paragraphs, several of the microphysical processes shown in Figure 2-5 are described and the key characteristics of the different particle types present in exhaust plumes given in more detail. Figure 2-5 is a schematic representation of the size distributions of the different plume particle types at a plume age of 1 s as inferred from measurements and models (Kärcher, 1999). In the diameter range below 10 nm, the overall number size distribution is dominated by the volatile nucleation mode containing particles, mainly composed of H_2SO_4 and H_2O (for fuel S contents above average values, which are of the order 0.4 g S/kg fuel).
- 2.4.4 Model results suggest that the volatile particle size distribution may exhibit a bimodal structure (Yu and Turco, 1997). Very recently, it became possible to measure directly the ultrafine particle size distribution above 3 nm diameter using a suite of condensation particle counters (Schröder *et al.*, 1998, 2000a) and these measurements strongly support the picture of new particle formation in young exhaust plumes, as postulated by Yu *et al.* (1999).

UNCLASSIFIED

- 2.4.5 The smaller particles are formed by aggregation of homogeneously nucleated clusters of hydrated H_2SO_4 molecules (neutral mode). The larger particles are formed by rapid scavenging of small molecular clusters by chemi-ions (ion mode). The growth of charged particles is preferred over the growth of neutral particles because of a net enhancement of the condensation and coagulation rates in a charged aerosol.
- 2.4.6 The concentration of cluster particles in the neutral mode depends strongly on the fuel S content. Their mean size is relatively invariant because of imperfect sticking of hydrated H_2SO_4 clusters after a collision. The mean size of the ion mode particles depends on the amount of material available for condensation. The concentration of the order 10^{17} ionised particles per kg fuel is relatively invariant, indicating that they form on virtually all of the emitted chemi-ions. Besides H_2SO_4 , which preferably condenses onto negative ions, organic exhaust species mainly condense onto positively charged clusters owing to their relatively large proton affinity. This implies that the ion mode actually consists of at least two modes (not resolved in Figure 2-4), and may contain exhaust hydrocarbons, besides H_2SO_4 and H_2O .
- 2.4.7 Aircraft jet engines emit soot particles. The term 'soot' encompasses all primary, carbon-containing products from incomplete combustion processes. Besides the pure (optically black) carbon fraction, these products may also contain non-volatile (grey) organic compounds. Exhaust soot is important in providing nuclei for liquid droplets or ice crystal formation; soot strongly absorbs radiation and potentially affects air composition.
- 2.4.8 Soot emission depends upon engine type, power setting and possibly on the state of engine maintenance. Döpelheuer (1997) gives an average soot emission index of 0.04 g soot per kg fuel for the present subsonic fleet, whereas older jet engines emit up to 1 g/kg. As mentioned by IPCC (Chapter 3), no significant dependence on soot emission index and fuel S content has been found (Petzold *et al.*, 1997; 1999a; Anderson *et al.*, 1998a; Paladino *et al.*, 1998).
- 2.4.9 Petzold *et al.* (1999b) recently compiled size distributions, microphysical and optical properties, and emission indices of soot particles measured behind different jet engines. The results seem to support the presence of two soot modes (as indicated in Figure 2-5), a primary mode with a mean diameter of 30 nm and a mode of agglomerated primary soot particles at 150 nm, with at least two orders of magnitude difference in number concentrations. The fine black carbon particles dominate the light extinction of the plume aerosol.
- 2.4.10 Field data indicate, at least for the aircraft types considered, that modern engines emit less soot particles by mass and number, and that the particles are somewhat smaller than those from old-technology engines.
- 2.4.11 Fresh soot particles are likely to become hydrophilic by activation from deposition of H_2O molecules and water-soluble species present in the exhaust, starting in the jet regime and perhaps even within the engines (Kärcher, 1998b). Irregular surface features can increase the adsorptivity and amplify nucleation processes. It is known that soot hydrates more effectively with increasing fuel S content (Hagen *et al.*, 1992). For average and high sulphur levels, H_2SO_4 is likely to be the primary soluble constituent on soot surfaces.
- 2.4.12 Figure 2-6 shows an electron microscope photograph of a soot and $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ particle mixture from *in situ* measurements in an exhaust plume. Soot and aqueous H_2SO_4 particles (the latter seen as faint spherical droplets) are visible in this sample, and sulphur has been detected in/on some of the soot particles, indicative of soot and sulphur interaction in young plumes which eventually leads to an internal aerosol mixture. The degree of mixing depends on plume age and concentration of background particles, among other factors. The large sulphate droplets are background particles entrained into the plume. The photograph also reveals the irregular structure of the larger soot particles (agglomerates). Although the F16 has a low bypass ratio² engine and is rather different to current higher bypass ratio civil turbofan engines, the illustration of a mixture of soot and sulphur particles remains valid.

² Bypass airflow divided by engine core airflow.

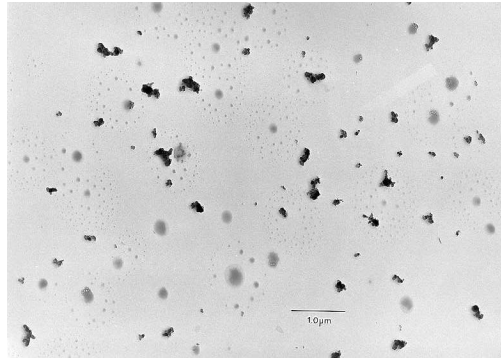


Figure 2-6 Exhaust particles from the plume of an F-16 aircraft in flight. Photomicrograph taken with a transmission electron microscope. Figure by P. Sheridan downloaded from the web site: www.cmdl.noaa.gov/aerosol/about/sheridan/particles.html.

- 2.4.13 Production of soluble material by soot and SO_2 interaction is only possible by assuming perfect sticking of SO_2 molecules and rapid heterogeneous conversion to sulphate on the carbon surfaces. However, sticking probabilities of gaseous SO_2 to amorphous carbon are too small to lead to significant surface coverages and time-scales in young exhaust plumes seem too short to allow heterogeneous H_2SO_4 production. However, SO_3 and H_2SO_4 molecules might easily adsorb on soot prior to volatile particle formation, and direct emissions of S(VI), as suggested by recent observations, may explain the measured soluble mass fractions on soot. Scavenging of small volatile droplets constitutes another soot activation pathway.

3 Identifying the uncertainties

3.1 “What are the uncertainties in mechanisms of contrail formation?”

Summary

- The high number of ice particles observed in contrails necessitates that particles emitted by the engines or produced in the plume trigger contrail formation. There are no basic uncertainties related to this issue.
- In terms of new particle production, the relative roles of sulphur, organic compounds and chemi-ions are not well understood. The role of organics in particle production is inferred from observations but the mechanisms and species involved, remain speculative. Even more poorly understood are the transformations that occur in the engine itself. This remains a basic uncertainty for the role of S species.
- Contrails could, hypothetically, form in the absence of soot and sulphate emissions from the engine by activation and freezing of background particles. However, such contrails may have different properties and these are unknown.
- Hydrogen powered aircraft would emit very few particles but a large amount of water vapour: if a future fleet were to be developed, more research would be needed to investigate the contrail properties.
- Freezing mechanisms are uncertain. The ice-forming properties of soot and volatile particles are poorly characterised. However, calculated contrail properties are not sensitive to uncertainties in freezing nucleation rates because of the high supersaturations reached in the plume.
- The impacts of contrails on the chemistry of the upper troposphere and lower stratosphere is thought to be small but there are basic uncertainties over chemical mechanisms and their importance. These do not, however, affect the formation of contrails themselves.

3.1.1 Particle production processes

- 3.1.1.1 Aircraft emissions result in direct and indirect emission of particles as described in detail in Section 2, i.e. non-volatile soot particles and volatile particles from new particle formation by gas-to-particle nucleation processes. Non-volatile metal particles are also emitted from wear of the engine but these have been shown to constitute only a small fraction of the number density of particles (e.g. Petzold *et al.*, 1998).
- 3.1.1.2 Contrails may form on the volatile and non-volatile particles in the aircraft exhaust plumes. Young contrails consist of water and ice particles that nucleate primarily on exhaust soot and volatile aerosol particles, owing to heterogeneous and homogeneous freezing processes.
- 3.1.1.3 The exact attribution of particles in the plume from different sources is not well understood: volatile particles originate from sulphur in the fuel, chemi-ions and possibly unburned hydrocarbons. Non-volatile particles originate from soot and metals.
- 3.1.1.4 Of the volatile particles, sulphate is the best characterised. However, although SO₂ and H₂SO₄ (the latter from binary homogeneous nucleation) have been detected in aircraft plumes (Arnold *et al.*, 1998; Curtuis *et al.*, 1998), the rates of reaction of SO₂ with OH (and subsequent) to form H₂SO₄ are too small to account for the observed particle numbers (Kärcher *et al.*, 1996; 1998). However, if SO₃ (from SO₂+O+M) is assumed to be present in the exhaust, then the agreement between models and observations improves. Whilst the formation of SO₃ within the engine itself is likely, it is unproven. Reaction rates of SO₂ + OH and the volume mixing ratios of O and OH are rather important and significant to the overall calculated efficiency of fuel-S conversion (Tremmel and Schumann, 1999). These remain large uncertainties.

- 3.1.1.5 Chemi-ions are formed in aircraft exhaust from ion production in high temperature combustion. Modelling studies have indicated that these may be important in promoting the formation and growth of molecular clusters containing H₂O and H₂SO₄ (Yu and Turco, 1997). Arnold *et al.* (1998) have detected negative chemi-ions in the plume of an engine under ground-level conditions. Using measurements of ultrafine particles (Schröder *et al.*, 1998), Kärcher *et al.* (1998a) and Yu *et al.* (1998) showed in model studies that a consideration of chemi-ions was necessary to explain the measurements. Clearly, chemi-ions require better characterisation and understanding of their importance in new particle formation.
- 3.1.1.6 More recently, there has been some discussion of the role of organics (i.e. not black carbon soot) in ultrafine particle formation by nucleation and condensation (Kärcher *et al.*, 1998b; Yu *et al.*, 1999). Organic compounds in gas turbine exhaust are not well characterised and there are only a few studies of composition and mixing ratios. However, from the few measurements that there are, it is clear that low-molecular weight alkenes, alkynes and aldehydes dominate. It should be noted that speciation and mixing ratios are a strong function of engine power setting. Yu *et al.* (1999) proposed that organics may play a role in particle formation. Critical in their argument are the solubilities of these species in water and acid solutions. This issue clearly needs more work.
- 3.1.1.7 Soot, i.e. black carbon, is emitted and particle concentrations, number densities and size characteristics have been measured at ground-level and in-flight (e.g. Petzold and Schröder, 1998; Petzold *et al.*, 1999b). Soot particle number densities are of the order two magnitudes lower than volatile particles (Anderson *et al.*, 1998a, 1998b; Schröder *et al.*, 1998). It is thought that soot particles can become activated and subsequently form water and ice particles either by direct deposition of water to them, or by initial coating with H₂SO₄. Soot emissions are rather better understood and characterised than volatile particles.
- 3.1.1.8 The above paragraphs consider only the direct emission of soot particles and chemi-ions from aircraft gas turbines from the exit plane into the hot jet and subsequent plume. However, it has already been alluded to that chemical conversions start in the combustor and turbine machinery of aircraft engines. These conditions and concentrations of critical species are virtually unknown: even exit-plane measurements are scarce. Most models of plume chemistry assume boundary conditions from either within the gas turbine or at the exit plane (e.g. Tremmel *et al.*, 1998; Tremmel and Schumann, 1999). If further progress is to be made in understanding particle formation, it is critical to have measurements with which hypotheses can be tested and models validated. This is being addressed, in part, by a planned engine simulation rig as part of the new EU Fifth Framework Program (5FP) project 'PARTEMIS'.
- 3.1.1.9 Contrails would also form in the absence of soot and sulphate emissions from the engine by activation and freezing of background particles. This is, of course, hypothetical and the answer relies on simulation results. However, there is no doubt that contrails would still form, albeit with different properties. Hydrogen powered aircraft would emit very few particles (i.e. only those from engine wear and particles taken in from the background atmosphere): if a future fleet was to be developed, more research would be needed to investigate the contrail properties (see Section 3.6). Some preliminary work is underway to investigate the environmental effects of a hydrogen-powered fleet of aircraft under the new 5FP project 'CRYOPLANE'.

3.1.2 Contrail properties and freezing mechanisms

- 3.1.2.1 This section discusses the microphysical properties of ice particles that have been deduced both from *in situ* measurements and modelling. The various freezing pathways in contrails are also discussed and the uncertainties highlighted.
- 3.1.2.2 According to *in situ* measurements using optical particle counters (Petzold *et al.*, 1997), young contrails (plume age 5–20 sec) have ice particle number densities of 10^4 – 10^5 cm⁻³ and mean diameters in the range 1–2 μm. Recent observations with improved instruments confirm that particle numbers increase toward smaller plume ages below one second (Schröder *et al.*, 2000a), as suggested by model results. A size distribution of such a nascent contrail measured *in situ* is shown in Figure 3-1.

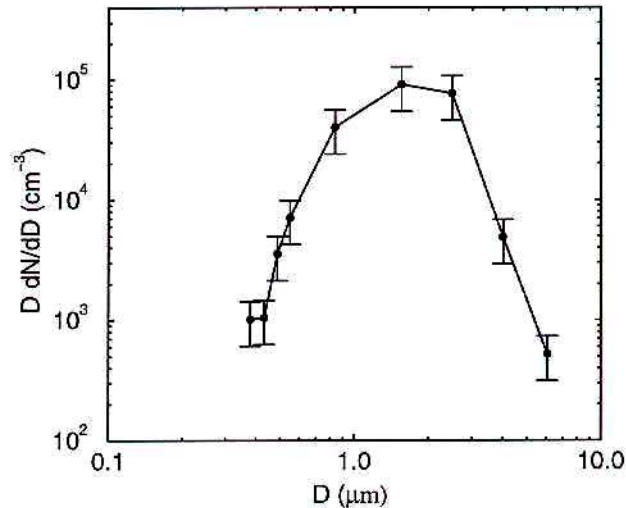


Figure 3-1 Ice particle size distribution and associated measurement uncertainties in a nascent contrail observed with an optical spectrometer in the plume of a B737 burning low sulphur fuel (2 ppm by mass). Data courtesy of Franz Schröder, adapted from Schröder *et al.* (2000a).

- 3.1.2.3 The observations confirm model simulations that predict an increase of initial ice particle concentrations from 10^4 – 10^5 cm^{-3} and a decrease of mean diameters from 2 μm to 0.6 μm when the ambient temperature is lowered by 10 K from a typical threshold formation value of 222 K (Kärcher *et al.*, 1998a). As noted before, these numbers do not strongly depend on the fuel S content. The simulations further suggest that contrails would also form without soot and sulphur emissions by activation and freezing of background particles, which are much less abundant than aircraft-produced particles. Therefore, the resulting contrails would contain larger particles. As a consequence, there is no obvious way to avoid or suppress contrails, except by seeding the plume with additional particles.
- 3.1.2.4 Gierens and Schumann (1996) reported a visible difference of colours of contrails with low and very high fuel S content. They explained this difference by a shift of the mean diameter of the ice particles from 1.5 μm to 0.7 μm , respectively. The simulations performed by Kärcher *et al.* (1998a) corroborate their explanation, suggesting that a combination of heterogeneous freezing of coated soot particles and additional homogeneous freezing of volatile solution droplets (in the case of very high fuel S content) is responsible for the colour change. The simulations further confirm the hypothesis of Schumann *et al.* (1996) that an increase of the fuel S content leads to a faster growth of the liquid coatings from an enhanced uptake of H_2SO_4 prior to freezing. Enhanced H_2SO_4 masses on the soot surfaces lead to faster freezing of the liquid coatings.
- 3.1.2.5 Both homogeneous and heterogeneous freezing processes are possible in contrails. Homogeneous freezing of pure water occurs in the absence of foreign substrate. Heterogeneous freezing occurs when a particle is contained within the droplet or is in contact with its surface. The most efficient freezing mode takes up the available (emitted) H_2O and prevents growth of other particle modes. Soot is expected to play an important role in the formation of contrails at and down to a few K below the threshold formation temperatures. Contrails observed under such conditions are explained to result from freezing of ice within water-activated soot particles. Volatile droplets are then prevented from freezing because the freezing of soot-containing particles is too rapid.

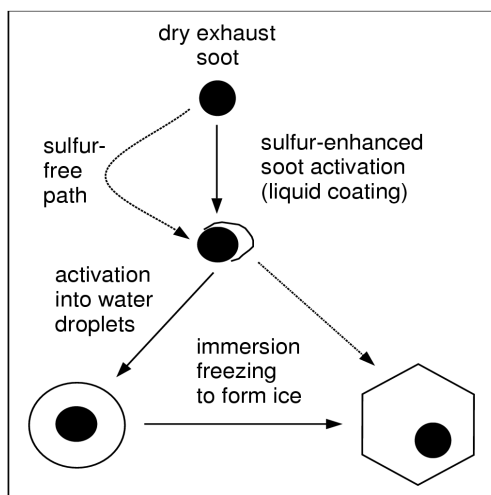


Figure 3-2 Soot-induced freezing (heterogeneous) pathway leading to contrails (Kärcher, 1998a). Soot particles acquire a (partial) liquid $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ coating due to adsorption of oxidised sulphur gases and scavenging of volatile droplets. They also trigger freezing if the fuel S content is very low (a few ppm by mass), suggesting an additional sulphur-free heterogeneous freezing mode (dashed arrow). Few ice particles may also nucleate without water activation (dot-dashed arrow). Soot dominates ice formation at and slightly below threshold formation temperatures. Homogeneous freezing may also occur and enhance the ice mass for lower temperatures and/or higher fuel S contents (not shown). Ice crystal shapes are close to spherical in young contrails, but may vary in ageing contrails as indicated by the hexagon. Soot cores may reside inside the crystals, or are attached at their surface.

- 3.1.2.6 Fresh soot particles do not act as efficient ice deposition nuclei in the exhaust because their surfaces are not well suited to initiate the direct gas-to-solid (ice) phase transition. This follows from the absence of contrails at temperatures above the liquid water saturation threshold. Water activation of soot may result from the formation of at least a partial coating of the soot surfaces with aqueous H_2O . Prior to contrail formation, this surface coverage increases with the fuel S content and leads to a greater number of ice particles. The acid coating will persist at the soot particle surfaces. Figure 3-2 sketches the heterogeneous freezing pathway leading to contrails.
- 3.1.2.7 Contrails formed at threshold conditions and very low (2 ppm by mass) fuel sulphur content contain soot particles with H_2SO_4 surface coverages of only 0.02% (Kärcher, 1998b), which raises the question as to whether the soot activation by sulphur gases supports heterogeneous freezing in such cases. This may point towards the formation of a pure water coating (dashed arrow in Figure 3-2) that is enhanced when the fuel sulphur level is increased to average values or higher. Such a process could explain the observed insensitivity of contrail formation and visibility to changes of the fuel S content for very low sulphur levels.
- 3.1.2.8 The mechanism of heterogeneous ice formation via liquid coatings on soot is mainly inferred indirectly from the observations and needs experimental confirmation. Unique evidence that soot is involved in ice formation is difficult to obtain from *in situ* measurements, because it is difficult to distinguish whether a soot particle caused freezing or whether it was scavenged by an ice particle that formed from homogeneous freezing. The first direct evidence was found in very young contrails that evaporated quickly: part of the evaporating ice crystals released their core particles into the plume and this caused an increase in the number of soot particles counted (Schröder *et al.*, 1998). Owing to the short time available between freezing and evaporation, the ice particles most probably formed on the soot cores, and soot scavenging by ice was inefficient.
- 3.1.2.9 The fraction of frozen volatile $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ droplets depends on the droplet composition (affecting homogeneous freezing rate), the evolution of H_2O supersaturation, and the possible competition with heterogeneous freezing processes involving soot. Near the threshold conditions, model results suggest that the volatile aerosol fraction does not become large enough to freeze (Kärcher *et al.*, 1995; 1998a), and heterogeneous freezing of activated soot particles initiates contrail formation.

- 3.1.2.10 The above discussion underscores that homogeneous freezing of volatile $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ droplets is not likely to account for sufficient ice particle production under condition close to the formation threshold temperature. This picture does not change when uncertainties in the homogeneous binary nucleation and plume mixing rates are considered, and hold even for a very high fuel S content of 3 g S/kg fuel (Kärcher *et al.*, 1995), and when the effects of chemi-ions is taken into account (Kärcher *et al.*, 1998a). The model predicts contrail formation by this mechanism only if the plume becomes water supersaturated, in which case homogeneous freezing competes with soot-induced freezing processes and also ambient particles may contribute to ice crystal nucleation.
- 3.1.2.11 In the temperature regime well below the formation threshold, $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ droplets larger than the threshold activation size (radii $>2\text{--}5$ nm) can be activated into water droplets in the contrail. The threshold activation size and hence freezing probability, depends on the maximum supercooling reached in the expanding plume. Decreasing ambient temperature and increasing ambient humidity both lower the threshold size and increase the homogeneous freezing rates. In this regard, volatile particles from the ion mode are more easily activated than those from the neutral mode, and, hence, play an important role in contrail formation (Yu and Turco, 1997).
- 3.1.2.12 Evidently, the roles and mechanisms of homogeneous and heterogeneous freezing remain a basic uncertainty in contrail formation. More experimental data are needed and, in particular, laboratory studies.

3.1.3 Processing of aerosols in contrails

- 3.1.3.1 The evolution of volatile particles in young contrail plumes differs greatly to dry plumes. As described above, a fraction of the volatile particles grows by water uptake and may then freeze. The ice particles grow in surface area from deposition of H_2O and efficiently scavenge part of the volatile and soot particles during their lifetime, even in short-lived contrails. As a consequence, contrails contain fewer of the small particles than dry plumes (Anderson *et al.*, 1998; Schröder *et al.*, 1998). After evaporation of the ice crystals, the residual soot and sulphate cores are returned to the atmosphere.
- 3.1.3.2 Particle processing in short-lived contrails is likely to lead to a modified aerosol size spectrum and probably composition (Yu and Turco, 1998), similar to the effect that cloud processing is known to have on aerosol properties. Figure 3-3 depicts particle spectra in an evaporating contrail from a simulation model. Both acid and coated soot particle size distributions exhibit distinct modes. Mode 1 and mode 2 represent the neutral and ion modes, respectively, after processing at a plume age of 20 s (recalling that the unperturbed modes are depicted in Figure 2-5 at a plume age of 1 s). Mode 3 at a diameter of ~ 30 nm is an activation mode resulting from water uptake by the largest of the ion mode aerosols; these aerosols did not freeze. Mode 4 at 80 nm is an accumulation-type mode that was processed through the ice crystals, that is, these particles went through a freezing-evaporation cycle. The soot modes 5 and 6 are created analogous to modes 4 and 3, respectively.

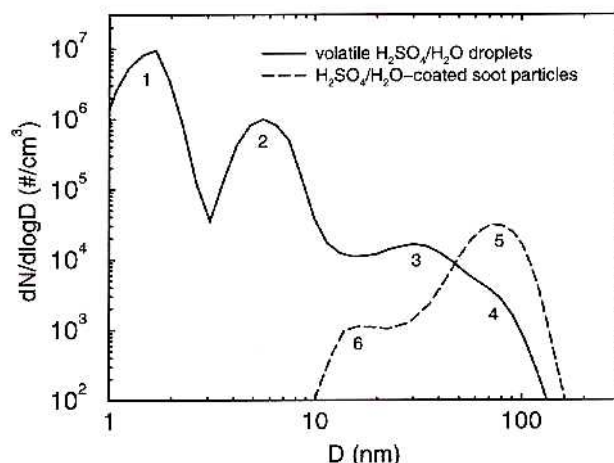


Figure 3-3 Simulated size distributions of acid (solid curve) and mixed soot/sulphate particles (dashed curve) in an evaporating short-lived contrail in a high sulphur plume at about 20 s plume age. Numbers denote distinct modes in the particle spectra, caused by coagulation processes between these particles and the contrail ice crystals. Data courtesy of Fangqun Yu, adapted from Yu and Turco (1998).

- 3.1.3.3 As conjectured by DeMott *et al.* (1999) on the basis of laboratory freezing experiments, the residual particles from evaporating contrails might be more efficient ice nuclei for cirrus formation than fresh, more hydrophobic soot. But even without formation of contrails, aircraft soot and sulphate particles enhance the atmospheric aerosol in terms of number and surface area densities (Kärcher and Meilinger, 1998; Yu and Turco, 1999; Anderson *et al.*, 1999). If only a small fraction of the abundant volatile particles were to grow to sizes sufficient to act as cloud condensation or ice nuclei, or the coated soot particles are more efficient freezing nuclei than the background particles, they could have important climatic implications from the additional formation of cirrus.
- 3.1.3.4 However, to track the evolution of aircraft particulates in the ageing plume over the time-scale of days is a difficult problem and depends upon the availability of atmospheric SO₂ and particles, among other details. It is noteworthy that, according to detailed microphysical simulations for relatively clean upper tropospheric conditions, reductions in the fuel S content may not efficiently reduce the number of climatically significant particles injected by aircraft (Yu and Turco, 1999). Unfortunately, the importance of such perturbations cannot be quantified at this time, mainly because of the lack of atmospheric measurements.
- 3.1.4 The potential chemical effects of aviation-produced aerosols and clouds in the atmosphere**
- 3.1.4.1 The chemical effects of soot and sulphate particles from current subsonic aircraft at cruise altitudes are poorly quantified. The contribution of subsonic aircraft sulphate to total upper troposphere and lower stratosphere (UTLS) sulphate seems to be small (e.g. IPCC, 1999) as is also the case with soot (approximately 1–10%). In this case, heterogeneous chemistry on aircraft-generated soot and sulphate particles may be of minor importance. However, the contribution of aircraft soot to total soot surface area in the UTLS is currently unknown. Moreover, the importance of heterogeneous chemistry on soot is rather uncertain (IPCC, 1999 Chapter 2).
- 3.1.4.2 Increases in lower stratospheric water vapour from aircraft operations may cause faster heterogeneous chemistry on background aerosol particles in the stratosphere which may be an issue should a fleet of supersonic aircraft be developed.
- 3.1.4.3 Chlorine activation reactions may occur on the surfaces of aerosols and cirrus clouds (Borrmann *et al.*, 1996). Thus, it is possible that contrails and contrail-induced cirrus may perturb O₃ budgets in this regions from heterogeneous chlorine chemistry.

- 3.1.4.4 Previous model studies investigating the potential chemical effects of supersonic aircraft in the stratosphere showed a large sensitivity of computed ozone depletion to the assumed properties of sulphate particles produced at emission. In the light of new results about limitations of heterogeneous chemistry on aviation-produced aerosols, these simulations should be revised. In the context of current subsonic aviation, soot-related chemistry may not require further research in the near future. In contrast, heterogeneous chemistry on ice surfaces should receive high research priority, because significant potential impacts of clouds on chemical balance have been identified. In this regard, a better understanding of the role of natural cirrus in the chemistry of the upper troposphere and lowermost stratosphere is required before the chemical impact of contrails can be fully addressed.
- 3.1.4.5 Finally, a modelling study of the interactions of aircraft NO_x emission with inorganic bromine chemistry has shown that—depending amongst other things, on aerosol loading—O₃ production rates may be increased in the lowermost stratosphere (Hendricks *et al.*, 2000).

3.2 “How much is known about cirrus cloud resulting from aircraft emissions, as opposed to ‘young’ persistent contrails?”

Summary

- Over the time scale of one hour, persistent contrails attain particle size distributions that resemble those of young, upper tropospheric cirrus clouds at mid latitudes.
- It has been demonstrated by satellite and *in situ* observations that linear contrails can transform into extended cirrus cloud decks.
- The extent to which contrail-cirrus and natural cirrus clouds differ from each other in terms of radiative properties is poorly understood.
- The evolution of cirrus clouds can potentially be modified by aircraft exhaust. For aircraft to alter cirrus properties, exhaust soot particles would need to be more efficient ice nuclei than the background particles existing within the same air mass.
- The potential coverage of contrail-induced cirrus and its radiative properties are unknown. This prevents an estimate of the associated radiative forcing.
- The residual particles from short-lived contrails might be more efficient ice-forming agents than fresh soot. However, the freezing behaviour of mixtures of soot and sulphate aerosols in ageing plumes or processed by contrails has not yet been studied systematically.

3.2.1 The origins of aviation-induced cirrus cloud

3.2.1.1 In this Section 3.2 it is necessary to distinguish the origins of cirrus clouds from contrails.

- The first and most straightforward mechanism is the transition of a persistent contrail into a cirrus cloud. This can be observed and has been studied.
- The second mechanism which is hypothesised—but not proven—is the later formation of cirrus cloud some time after the aircraft has passed and when the air mass undergoes changes in temperature and relative humidity conditions, the basic tenet being that the cirrus would not have formed without the aircraft particles.

3.2.1.2 In the second mechanism, there are two cases to be considered: when no contrail forms and the particles later trigger cirrus formation; and when a short-lived contrail processes the particles potentially altering the propensity of those particles to later trigger cirrus cloud.

3.2.2 The transition of persistent contrails into cirrus cloud

3.2.2.1 Contrail persistence is primarily linked to synoptic conditions that support vertical motions of air, such as frontal zones connected with the warm sector of lows, jet streams that carry moist air across stable highs, and flows induced by mountain waves. Under these conditions the relative humidity may exceed ice saturation, promoting depositional growth of the contrail crystals. Contrail ice crystals evaporate quickly when the ambient air is subsaturated with respect to ice, unless the particles are coated with certain substances such as HNO₃ (Diehl and Mitra, 1998). Contrail spreading may be induced by vertical wind shear, especially in contrails with a large vertical extent caused by updrafts driven by radiative heating.

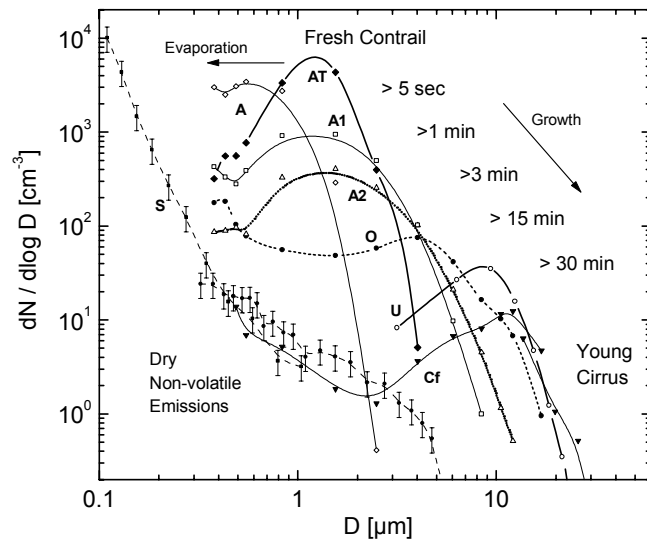


Figure 3-4 Representative selection of observed size-resolved particle concentrations illustrating the transition of contrails into young upper tropospheric cirrus clouds. S: exhaust soot spectrum in a plume without contrail. A: Evaporating, short-lived contrail. Cf: Young cirrus cloud. Others: Persistent contrails at different plume ages. Figure taken from Schröder *et al.* (2000b).

- 3.2.2.2 Figure 3-4 shows a representative selection of observed particle concentrations illustrating the transition of contrails into cirrus clouds (Schröder *et al.*, 2000b). The contrails were sampled in the upper troposphere over Germany at altitudes between 9.5 and 11.5 km. Shown are a fresh contrail (labelled AT), an evaporating short-lived contrail (A), few minutes old, persistent contrails (A1, A2), one older than 15 minutes (O) and one older than 30 minutes (U). For comparison, soot emissions (taken in an exhaust plume where no contrail formed) and a young cirrus cloud (i.e. large number density of small crystals) mode are also shown with labels S and Cf, respectively.
- 3.2.2.3 Contrails with progressively increasing age (from AT to U) exhibit a continuous decrease of ice crystal concentrations from $> 2000 \text{ cm}^{-3}$ to about 10 cm^{-3} caused by plume dispersion. At the same time, their mean diameters increase from initially $1 \mu\text{m}$ to about $8 \mu\text{m}$, within the time-scale of about 30 minutes to 1 hour, close to the typical size of crystals in young cirrus. The variability of observed spectra is high in the near field. The variability is smaller at later stages, mainly controlled by ambient temperature and humidity. Observations and model estimates suggest that contrail growth is only weakly affected by pre-existing cirrus on these time-scales.
- 3.2.2.4 The growth of the ice crystals in the persistent contrails was such that the measured surface area densities of the clouds stayed approximately constant, implying that the reduction of the crystal number owing to dilution effects was compensated by condensational growth of the ice crystals. Considering the observed variability in observations together with experimental uncertainties, the data suggest a range of $3500 \mu\text{m}^2 \text{ cm}^{-3} \pm 40\%$ as a characteristic value for the persistent contrails on time-scales of a few minutes up to an hour. Since the Mie scattering coefficient (calculated for a wavelength of $0.5 \mu\text{m}$) is only weakly varying for particles larger than a few micrometers, this implies that the optical extinction of persistent contrails is comparable with that of young cirrus (mean diameter $\sim 10 \mu\text{m}$), variable within a factor of three.
- 3.2.2.5 However, optical depths³ and radiative forcing may differ by larger factors because of different geometric properties. The variability of environmental conditions and contrail ages were limited for the suite of contrails observed by Schröder *et al.* (2000b) and contrails may evolve differently in a warmer or colder environment or over longer time-scales. *In situ* observational evidence is poor for such cases (e.g. Heymsfield *et al.*, 1998; Jensen *et al.*, 1998a). For example, the contrail de-

³ Or optical depth (τ), terms used interchangeably. This is the logarithm of the ratio between incident and transmitted radiative flux through a transparent layer of gases or particles.

scribed by Heymsfield *et al.* (1998) contained very few (<0.1 crystals per litre) ice crystals with sizes up to 300–500 μm at its periphery (resembling ambient developed cirrus in this respect), in addition to the many small particles present within the contrail core. The measurements suggest that a small fraction of core particles became mixed into the supersaturated contrail edges and grew, eventually forming precipitation streamers (virga). Jensen *et al.* (1998a) discussed a contrail observed at 212 K which had a complex microphysical structure. Other aspects about contrail-cirrus have been reviewed by Schumann (2000b).

3.2.2.6 Whilst size distributions of contrail ice crystals have been measured in some detail, optical measurements of shapes and light scattering properties of ice crystals in cirrus and contrails are sparse (e.g., Lawson *et al.*, 1998; Gayet *et al.*, 1998; Liou *et al.*, 1998). Given the wide range of environmental conditions under which persistent contrails may develop, which have not yet been fully explored by observations, it is difficult to assess to what extent contrails and natural cirrus clouds differ from each other in terms of radiative properties. A detailed comparison is further rendered difficult because cirrus is usually highly structured, especially those clouds at mid-latitudes, and freezing occurs sporadically and on a localised basis. This is an issue addressed further in Section 3.7.

3.2.2.7 Numerical simulations of cloud formation and development have also been made. Gierens and Jensen (1998) performed simulations of the transition of a contrail into a young cirrus cloud using measured profiles of wind and temperature in an environment slightly above ice saturation. Figure 3-5 depicts the transformation at contrail ages of 6 s, 150 s, and 30 min. Shown are contour lines of ice water content in units of mg ice per m^3 of air versus altitude (vertical axis) and horizontal extent (horizontal axis), both in metres. It is noted that while the first plate (6 s) shows the two contrails as they evolve from the wing-tip vortices, the second plate (150 s) depicts water ice originating from the secondary wake. The secondary contrail cloud forms from upward-moving air detrained from the vortices; the vortices rapidly sink and become adiabatically compressed and heated, leading to the disappearance of the primary contrail structure. This effect has been observed by lidar measurements (Sussmann and Gierens, 1999) and appears preferentially behind heavy airliners with four engines.

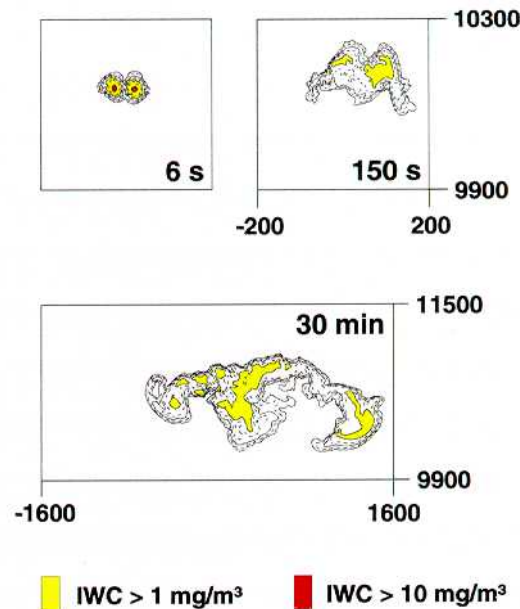


Figure 3-5 Transformation of a contrail into a cirrus cloud. Two-dimensional large-eddy simulation using observed wind and temperature profiles, assuming moderate ice supersaturations. Vertical axis: altitude (in m), horizontal axis: contrail width (in m), contour lines: ice water content (in mg/m^3). Figure courtesy of Klaus Gierens, adapted from Gierens and Jensen (1998).

- 3.2.2.8 Figure 3.5 shows that the contrail spreads in both directions while the ice particles grow by taking up ambient water vapour. Growth in vertical extent, even up to 400 m into a dry layer above the flight level, is strong in the first stage of contrail evolution, driven mainly by the prescribed temperature profile. After 15 min, the contrail disperses horizontally, reaching a width of 2 km at the end of the simulation. The evolution of the simulated crystal size distributions at the positions of maximum ice water content (not shown) reveals a striking similarity with those shown in Figure 3-3, achieving mean sizes of the order 10–20 μm . This increases confidence in such types of simulations.
- 3.2.2.9 However, some contrail ice crystals can reach much larger sizes, as noted above. Simulations of a contrail spreading and growing in a sheared environment have been presented by Jensen *et al.* (1998b). In simulations with large relative humidities over ice (above 125%)—such as those frequently observed in the upper troposphere—crystals with lengths exceeding 100 μm are generated by depositional growth, in accordance with observations. These large crystals fall rapidly, and significant horizontal spreading occurs primarily as a result of crystal precipitation in conjunction with vertical wind shear. Strong radiative heating (up to 10 K per day) in the contrail region enhances vertical mixing.
- 3.2.2.10 These simulations highlight the need for further systematic measurements of optical properties and model studies of persistent contrails. For example, ice crystal properties, contrail spatial structure and radiative heating, and generation of precipitation depend strongly on contrail and surface temperatures, ambient humidities, wind shear, the presence of clouds below the contrail, among other factors. The dependencies and the sensitivities associated with each of these parameters have not been studied in detail.
- 3.2.2.11 It is difficult to assess to what extent contrails and natural cirrus clouds differ from each other in terms of radiative properties. While it has been demonstrated by satellite and *in situ* observations that linear contrails can transform into extended cirrus cloud decks, the abundance and possible range of microphysical and radiative properties of contrail cirrus has not yet been explored. This renders reliable estimates of the associated radiative forcings and efforts to develop parameterisation schemes for use in global models difficult. To resolve this issue, future research is needed.

3.2.3 The triggering of cirrus cloud from aircraft particles

- 3.2.3.1 Soot particles originating from aircraft exhaust may act as freezing agents and form cirrus clouds under atmospheric conditions where otherwise no cloud would form. Such a perturbation could lead to an expansion of cirrus cover, changes of microphysical and optical properties of clouds, and the associated radiative forcing (Jensen and Toon, 1997). *In situ* measurements of upper tropospheric cirrus clouds in regions of dense air traffic have clearly shown an enhancement of the ratio between ice crystal and aerosol number densities in regions of cirrus where the crystals contain relatively high amounts of absorbing material, presumably aircraft-derived soot (Ström and Ohlsson, 1998). Specifically, for the same number of aerosol particles, perturbed clouds contained 1.6 to 2.8 times more ice crystals than unperturbed clouds. This suggests that the enhancement of crystal concentrations is linked to aircraft soot emissions. The detailed mechanism causing this enhancement cannot be inferred from the observations.
- 3.2.3.2 For aircraft to alter cirrus properties, exhaust soot particles would need to be more efficient ice nuclei than the background particles existing within the same air mass. If the predominant atmospheric particles that freeze are composed of liquid $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$, aircraft soot particles could exert an impact on cloud formation at low temperatures (<220 K) if they exhibit the same freezing properties as the carbon surfaces investigated in the laboratory (DeMott *et al.*, 1999). This is because sulphate particles require a relatively high supersaturation before freezing occurs (Koop *et al.*, 1999). If the predominant atmospheric particles that freeze are good freezing nuclei, then soot from aircraft will only have a small, or negligible, impact on cirrus. The number of such heterogeneous freezing nuclei that are active at warm (>230 K) temperatures is not always small in the upper troposphere, as demonstrated by DeMott *et al.* (1998). The magnitude and importance of such potential modifications is not well understood.

- 3.2.3.3 Cirrus clouds may also be modified by enhanced sulphate aerosols but only larger particles (>50–100 nm) are efficient. Such large particles may originate from ambient particles enlarged by growth from H₂SO₄ (via aircraft-emitted or ambient SO₂) or by processing of liquid aerosols in short-lived contrails (for example as shown in Figure 3.3). It is well-known from model studies that large sulphate particles, such as those produced within the Mount Pinatubo volcanic cloud, could lead to a significant increase in number of ice crystals, optical depth, and radiative forcing of cirrus. Such modifications would predominantly occur in cold cirrus (<220 K), weakly forced by slow updrafts, and would require a large increase in the number of large sulphate particles.
- 3.2.3.4 The evolution of cirrus clouds can potentially be modified by aircraft exhaust. For aircraft to alter cirrus properties, exhaust soot particles would need to be more efficient ice nuclei than the background particles existing within the same air mass. The residual particles from short-lived contrails might be more efficient ice-forming agents than fresh soot. However, the freezing behaviour of mixtures of soot and sulphate aerosols in ageing plumes or processed by contrails has not yet been studied systematically. Further, sulphate aerosol enhanced or modified by aircraft emissions may also alter cirrus properties. Such modifications would predominantly occur under cold conditions and with weak dynamical forcings, and would require a large increase in the number of large sulphate particles. Because it is unlikely that aircraft sulphur emissions will cause large increases of the large background particle fraction, soot particles coated with sulphate or entrained into sulphate droplets are likely to be more important in forming new or modifying existing cirrus. The research priority should be high.

3.3 “How do changes in aircraft engine technology affect contrail formation?”

Summary

- The development of modern high bypass ratio turbofan engines with higher propulsive efficiencies has decreased exhaust gas temperatures.
- Cooler exhaust temperatures increases the vertical extent over which contrails form. Given the importance of the effects of propulsive efficiency on contrail formation, this effect needs to be better understood than it is at present, as only one experiment has been undertaken that demonstrates this.
- If a significant fleet of hydrogen powered aircraft is developed in the future, contrail coverage can be expected to increase because of the higher emission of water vapour. There are large uncertainties in the details of this, but few in the overall conclusion.

3.3.1 Engine and fuels technology

3.3.1.1 In this section, the discussion is focussed upon changes in engine technology and/or fuel. The typical modern engine for an aircraft is either a high bypass ratio turbofan or a turboprop. Turbo props do not generally fly at altitudes high enough to cause contrails. The bulk of the modern civil fleet is equipped with high bypass ratio turbofan engines. Some aircraft are still equipped with turbojet engines but these are becoming fewer with modern regulations on LTO (Landing Take-Off cycle) emissions and noise. The standard fuel used almost universally is kerosene although experimental aircraft have used hydrogen as a fuel. Kerosene has sulphur in the fuel, either as an inherent part of the refining process or as an additive. Sulphur in the fuel is limited by ICAO to 0.3% (by mass) but most fuels contain S in the range of 0.04–0.06%, much lower than the maximum allowed. Fuel additives are generally organic and contain small amounts of S and N. However, additives are being developed that may also contain other species.

3.3.1.2 For a much more detailed review of fuels and engine technology, the reader is referred to IPCC (1999) Chapter 7.

3.3.2 The effects of changes in conventional engine technology

3.3.2.1 Bypass ratios of turbofan aircraft engines have increased over the past 20 years. This has increased fuel efficiency and reduced engine noise. Increasing the bypass ratio of turbofan engines also has the effect of increasing the propulsive efficiency of the aircraft.

3.3.2.2 Higher bypass ratios have led to cooler exhaust temperatures, which in turn lowers the threshold temperatures for contrail formation. The overall effect of this is that contrails form at higher ambient temperatures for more efficient engines because a smaller fraction of the combustion heat is released into the plume and causes higher relative humidities. This was first pointed out by Schumann (1996) and was expanded upon in the IPCC (1999, Chapter 3) report but was somewhat contentious.

3.3.2.3 Recently, Schumann (2000a) has elaborated the argument by careful explanation of the underlying thermodynamics from first principles. Moreover, Schumann *et al.* (2000) have demonstrated this effect convincingly from observations of a modern Airbus 340 with CFM56-5C2 engines flying alongside an older Boeing 707 with PW JT3D-3B engines. The newer technology Airbus formed clearly visible contrails, whilst the Boeing did not.

3.3.2.4 The implication of the above is that as bypass ratios, and hence propulsive efficiencies increase, aircraft will have a greater propensity to form contrails (Schumann, 1996). This has been calculated to have a significant effect in a future scenario, which assumed an overall improvement of propulsive efficiency to 0.5 from present-day values of approximately 0.3 (Gierens *et al.*, 1999).

- 3.3.2.5 The above findings are of particular significance as they allow a revised and more accurate description of the formation of contrails. The so-called Schmidt-Appleman criterion (temperature vs water partial pressure) has been used for nearly five decades to predict contrail formation but in numerous studies, contrails have been found to form when the criterion excludes them. However, once the propulsion efficiency is taken into account, the agreement between theory and observations is improved.
- 3.3.2.6 However, of more significance is the utilisation of such data in predicting contrail formation by current and future fleets: accurate predictions of the atmospheric impact depends upon how reliably meteorological models can predict regions in the atmosphere prone to contrail formation. At present, this is rather poor. Moreover, future research needs to be committed to improving the predictive capability of large-scale models in terms of a better representation of the location of the tropopause, water vapour and temperature fields, cirrus clouds, and chemistry in the tropopause region (high research priority). This is dealt with in more detail in Section 3.7.
- 3.3.2.7 Whilst the study of Schumann *et al.* (2000) corroborates the theory described by Schumann (2000a), more data are required of a similar type to better quantify the variability of the effect.

3.3.3 Effects of potential future engine technologies with hydrogen fuel

- 3.3.3.1 If liquid hydrogen were to become a viable future option as a civil aviation fuel instead of kerosene, this would have an implication for the abundance of contrails. The use of hydrogen fuel would substantially lower the formation threshold temperatures. Contrail formation cannot be avoided or suppressed, except by massively seeding the exhaust with efficient ice-forming nuclei. This would form a large number of particles that would be less likely to form ice nuclei.
- 3.3.3.2 Modelling studies have predicted that contrails would form on background aerosol particles such that hydrogen fuel, whilst being virtually particle-free, would still produce contrails. Contrails forming on background aerosol particles without aircraft soot and sulphur emissions are likely to contain fewer but larger ice crystals (Schumann, 1996). It is conceivable that the microphysical variability of contrails forming exclusively on ambient particles is higher, because of the variability of number and freezing properties of particles in the air at cruise altitudes. However, as in the case of seeded contrails, the detailed properties of such contrails are essentially unknown. Future research on such properties would be necessary if future engines were to be fuelled by liquid hydrogen.
- 3.3.3.3 Recently, Marquart *et al.* (2000) have described the results of a modelling study which is in essence, a sensitivity study of extreme scenarios, the scenarios not being intended to represent a foreseen reality. It was assumed that in the 'conventional' scenario, the global fleet grows until 2015 and there is a constant fleet thereafter. In the cryoplane scenario, the whole conventional fleet is instantaneously and completely replaced with cryoplanes at a constant level thereafter. These scenarios were not intended to be realistic but illustrative of effects. The contrail abundance for the cryoplane fleet is larger: the global mean contrail coverage was calculated to be 0.235% for the conventional fleet and 0.366% for the cryoplane fleet. The resultant RF in 2015 was calculated to be 0.081 W m^{-2} for the cryoplane fleet compared to 0.052 W m^{-2} for the conventional fleet.

3.4 “Is the quantification of contrail coverage adequate?”

Summary

- The quantification of global contrail coverage is poor. There are no measurements for the globe, only a few particular regions.
- Persistent contrail coverage is a major uncertainty that propagates into calculations of RF. The only reliable data available are from satellite observations and only two such studies have been carried out, both in Europe. This situation should be easily and urgently rectified.
- Improved detection algorithms require development that can better detect aged persistent contrails. At present, only line-shaped structures can be accurately detected and discriminated from cirrus. A study of the contrail–cirrus transition may elucidate whether improvements with current technology are possible.

3.4.1 The current situation.

- 3.4.1.1 Estimates of the present-day (1992 base year) global coverage of contrails are based upon an extrapolation of contrail coverage from satellite observations over Europe (Sausen *et al.*, 1998). This technique has also been used for estimating potential coverage in 2050 (Gierens *et al.*, 1999).
- 3.4.1.2 From observations from AVHRR (Advanced Very High Resolution Radiometer) infrared images taken between 1979–81 and 1989–92 over Europe and the northeast Atlantic (30° W–30° E, 35° N–75° N), a mean contrail coverage of 0.5% was determined (Bakan *et al.*, 1994). More recently, Mannstein *et al.* (1999) have determined a value of 0.5% for central Europe using a contrail detection algorithm for satellite data. These two observations are inconsistent since the Bakan *et al.* (1994) observation scales to a value of 1.8% for the central European region measured by Mannstein *et al.* (Gierens *et al.* 1999). Mannstein *et al.* (1999) acknowledge that the algorithm can only detect linear contrails and may fail in places providing possible explanations for the disparity in values. Taking the value of 0.5% contrail coverage for Europe from Bakan *et al.* (1994), this then results in an estimated global contrail coverage of 0.1% (Sausen *et al.*, 1998). The normalisation of the results on European observations (0.5%) is a major assumption in Sausen *et al.*'s (1998) coverage calculation.
- 3.4.1.3 It has been shown that cirrus and line-shaped contrails have differing ice crystal size distributions (Betancor-Gothe and Grassl, 1993) and that it is possible to distinguish between them in satellite imagery using the split-window method (Betancor-Gothe and Grassl, 1993, Minnis *et al.* 1995). However, this distinction may well break down in the transition from line-shaped persistent contrails to cirrus clouds. Gierens and Jensen (1998) showed in a numerical simulation that the ice crystal size distribution of a contrail evolves towards that of a normal cirrus cloud before eventually disappearing. Current contrail coverage measurements do not account for cirrus that has evolved from contrails. It is likely, therefore, satellite detection methods that can only discriminate line-shaped features will underestimate persistent contrail coverage.
- 3.4.1.4 Very recently, first results have been shown from a North American study of contrail coverage (Minnis *et al.*, 2000). As yet, not enough details are available to comment on this study, although they are expected soon.

3.4.2 Areas of improvement

- 3.4.2.1 Estimates of global persistent contrail coverage are constrained by observations. Palikonda *et al.* (1996) reported measurements over the continental US from AVHRR data and Minnis *et al.* (1997) from surface observations. Further regional studies of critical global regions will help to reduce uncertainties. However, surface observations are unlikely to improve data quality quantitatively as observer variance and reliance on clear-sky conditions are critical constraints.

3.4.2.2 There are two factors that could help to reduce the uncertainty in contrail coverage: firstly, improving detection algorithms for analysis of satellite data and secondly, increasing the number of samples for locations along with improved temporal resolution.

3.4.2.3 A contrail detection algorithm for remote sensing data has been described by Mannstein *et al.* (1999). However, this has the limitation that it can only detect linear features. By use of satellite imagery, Palikonda *et al.* (1996) showed that over a period of hours, contrails can be advected such that they cover a large area and become indistinguishable from natural cirrus (Schumann and Wendling, 1990; Minnis *et al.*, 1998). This is the primary cause of uncertainty in coverage measurements. This is illustrated in Figure 3-6 below (from Minnis *et al.*, 1998).

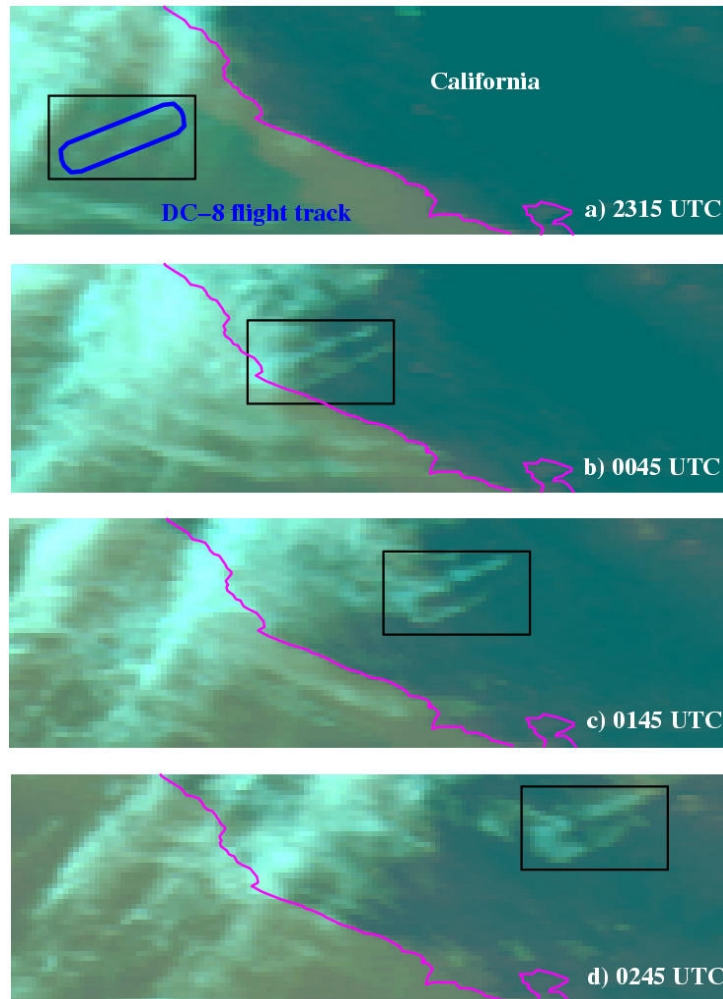


Figure 3-6 Evolution of contrail-cirrus formation from satellite imagery arising from NASA DC8 flight track (Minnis *et al.*, 1998).

3.4.2.4 Whilst it may be possible to improve detection of curvilinear features through the use of novel image processing techniques, it is unlikely that an algorithm could be designed to detect aged contrails from current knowledge of contrail microphysics. The use of frequent data from geosynchronous satellites to track the transition of contrails to cirrus would be the best method to analyse this problem to determine whether detection algorithms could be improved. However, the original imagery quality must also be considered and whether the spatial resolution is adequate.

3.4.2.5 There is currently only one algorithm for automated contrail detection, devised by Mannstein (described in full in Manstein *et al.*, (1999) which has also been used and modified by Minnis *et al.* (1995). This algorithm was devised for the satellite-based sensors AVHRR-HRPT, and ATSR. Comparisons made between AVHRR and GOES (Geostationary Operational Environmental Satellite) imagery (Young *et al.*, 1998) suggest that whilst the derived effective ice particle diameters and cloud-top temperatures were in good agreement, the derived optical depths were

UNCLASSIFIED

and cloud-top temperatures were in good agreement, the derived optical depths were not. A comparison of contrail coverage results derived from different detection algorithms and imagery sources would allow an assessment of the relative accuracies of each combination. This information is vital when combining statistics from a number of sources.

- 3.4.2.6 A study into the detection efficiency of contrails over land as compared to sea should be made since variations in land surface emissivity and surface temperature will affect the measured radiance through thin cloud. Likewise, detection efficiency over snow also needs to be studied.

3.5 “Are trends in global cirrus cloud coverage connected with trends in air traffic?”

Summary

- We do not know whether trends in global cirrus cloud coverage are causally linked to trends in air traffic.
- There is limited circumstantial evidence for this link but many other factors may be important in the apparent and convincing increase in cirrus coverage over the past three decades.
- Given that one of the RF bars on the IPCC radiative forcing figure (Figure 2 in the IPCC SPM) arises from this very question and no best estimate of the radiative forcing value could be given by IPCC, this question remains open and one of the largest uncertainties in the potential effects of aviation on global climate.
- The key to reducing the uncertainties would be to establish a causal link between air traffic and cirrus coverage increases or at least increase confidence in the inferred causality. Secondly, if this causal link is established, it is clear that better quantification of optical density of the aviation-induced cirrus is required in order to reduce uncertainties in the radiative forcing calculation. This requires carefully designed field studies.

3.5.1 Trends in air traffic and potential effects of aircraft emissions on cloud condensation nuclei

3.5.1.1 Air traffic has undergone very rapid expansion since the late 1950s. Growth rates in terms of Revenue Passenger Kilometres–RPK, were of the order 15% per year in the 1970s, 9% in the 1980s slowing to around 5% per year at the present and are projected to remain at such growth rates until 2015 (Brasseur *et al.*, 1998). These growth rates have varied regionally and are projected to do so in the future.

3.5.1.2 The basic hypothesis behind the question posed in this Section (3.5), is that additional cloud condensation nuclei (CCN) are injected into the upper troposphere and lower stratosphere by air traffic emissions and that these CCN may be responsible for triggering cirrus clouds which would not have formed in the absence of air traffic.

3.5.1.3 Cirrus clouds are known to exert a powerful effect on climate as they significantly impact the atmospheric radiation budget. The radiation budget affects the global circulation pattern, and thus climate (Liou, 1986; Lohmann and Roeckner, 1995). Thus, if air traffic results in additional or increased coverage of cirrus, then a positive RF may ensue. In the following subsections, the origin of the RF values for 1992 and 2050 for aviation-induced cirrus increases are examined and the associated uncertainties identified.

3.5.2 The magnitude of estimated 1992 and 2050 RFs for increases in cirrus

3.5.2.1 In IPCC (1999, Chapter 6), whilst an estimate was made of the potential RF associated with persistent contrails, only a spread of possible values was made for the impact of aviation particles on global cirrus coverage.

3.5.2.2 The sign given to this aviation-induced RF is positive, on the basis that cirrus clouds generally exert a positive forcing. However, such positive forcing may not be so clear-cut. Ström and Ohlsson (1998) found that soot emissions in a highly trafficked atmosphere caused a doubling of ice particle concentrations. Small particles result in a larger optical depth for constant ice water content (Table 3.7, IPCC, 1999 Chapter 3). An increase in optical depth results in additional heating if the cirrus cloud is optically thin but cooling if optically thick (Wyser and Ströhm, 1998). Thus the sign of the potential RF is dependent on the cirrus cloud itself.

- 3.5.2.3 The origins of the maximum of the IPCC estimate for aviation-induced cirrus coverage increases of 0.04 W m^{-2} (1992) is as follows. Additional global cirrus coverage was assumed to be 0.2% (an upper bound for 1992); the optical thickness of additional cirrus is assumed to be the same as line-shaped persistent contrails, i.e. 0.3. This leads to an estimate of a RF of 0.04 Wm^{-2} .
- 3.5.2.4 For the assessment of 2050 aviation-induced cirrus coverage, IPCC (1999, Chapter 3) adopted a different approach. A correlation between cirrus coverage and aviation fuel consumption was used to extrapolate an increased global cirrus coverage of 0–0.8%. Assuming the same radiative sensitivity, a range of 0– 0.16 W m^{-2} was speculated.
- 3.5.3 Major uncertainties in calculating RF from aviation-induced cirrus**
- 3.5.3.1 The RF values calculated for 1992 and 2050 by IPCC were by different methods and thus have different uncertainties.
- 3.5.3.2 The uncertainties arising from aviation-induced cirrus for the **1992 RF value** arise from the estimate of additional global cirrus coverage and the assumed optical thickness.
- 3.5.3.3 The calculated 1992 additional cirrus coverage involves an a priori assumption that trends in cirrus are the result of air traffic. This assumption is questionable and is considered in more detail below. This assumption results in a calculated additional global cirrus coverage of 0–0.2% over that prior to the advent of jet aviation.
- 3.5.3.4 The second major assumption in the calculation of the aviation-induced cirrus for the 1992 RF value arises from an assumed optical thickness (0.3) that is the same for line-shaped persistent contrails.
- 3.5.3.5 The optical thickness in the solar range (near a wavelength of $0.55 \mu\text{m}$) for persistent contrails is typically in the range 0.1–0.5 (Kästner *et al.*, 1993; Jäger *et al.*, 1998; Minnis *et al.*, 1998; Sassen, 1997; cited in Meerkötter *et al.*, 1999). Persistent contrails are typically several 100 metres deep and can sometimes increase the optical thickness to larger values, i.e. > 1.0 . The net RF (sum of long and short-wave radiation) sensitivity to optical thickness was investigated by Meerkötter *et al.* (1999) and is shown below. It can be seen from Figure 3-7 that the flux change is rather sensitive to optical depth. The uncertainty in optical depth is estimated to be a factor of 2–3 for RF values calculated for persistent contrails (Meerkötter *et al.*, 1999). At the surface the overall flux is negative, where the net flux is dominated by sort wave radiation, whereas the net flux is positive at the top of the atmosphere where the flux is dominated by long wave fluxes.

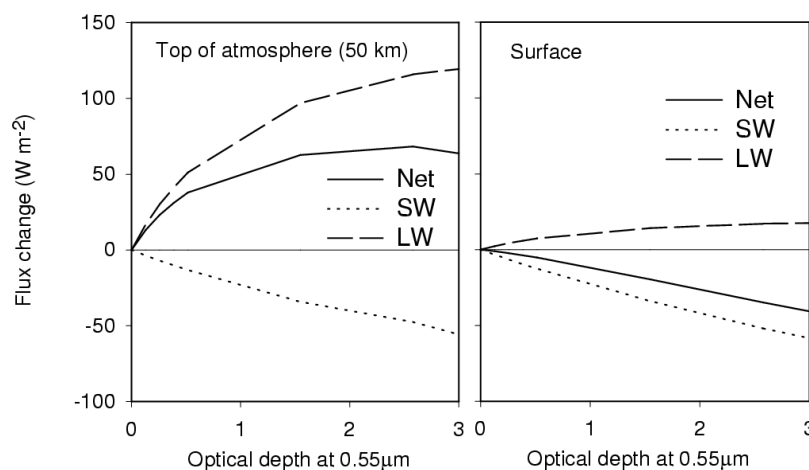


Figure 3-7 Shortwave (SW), longwave (LW) and net instantaneous radiative flux change from contrails with 100% cover under mid-latitude summer conditions averaged over a day as a function of optical depth ($0.55 \mu\text{m}$): near the top of the atmosphere (50 km) and surface (0 km). From Meerkötter *et al.* (1999).

UNCLASSIFIED

- 3.5.3.6 The uncertainties arising from aviation-induced cirrus for the **2050 RF value** arise from the correlation between increases in aviation traffic and trends in cirrus coverage and the fuel usage. Fuel usage is a surrogate for aircraft movements, which is discussed elsewhere (see Section 3.6). Fuel usage is a function of the scenario adopted (in the case of the RF for 2050, Fa1) and has a different kind of uncertainty.
- 3.5.3.7 The most critical of these factors is the postulated relationship between increases in air traffic and increases in global cirrus coverage. This is discussed in some detail below.
- 3.5.3.8 The IPCC report (1999, Chapter 3) reviews the evidence for increases in cirrus coverage. Although the studies vary in the quality of data used (surface observers through to systematic satellite observations), there is good evidence for increases in cirrus cloud over the last 30 years or so. The critical question is whether the increase in aviation is a causal factor in this increase in cirrus coverage. The question is *not* whether they can be correlated, as this is very poor circumstantial evidence of a causal link. One of the key difficulties is that there are a variety of factors that may contribute towards increases in cirrus coverage including increases in tropopause height, increases in upper tropospheric relative humidity etc. (see IPCC, 1999 Chapter 3, Section 3.5.3). These factors may or may not be caused by climate change.
- 3.5.3.9 Chapter 3 of IPCC (1999) presents an extensive analysis of available data on contrail coverage (as computed by the method of Sausen *et al.*, 1998). Trends (% per decade) were calculated for computed contrail coverage of greater than, and less than 0.5%. The difference between these categories, and the statistical difference, was then calculated. The results are rather variable but where statistically significant (globally and over land only), vary between 1.6 and 3.5% per decade.
- 3.5.3.10 The key publication in this debate is that of Boucher (1999) published in *Nature*. The main conclusion of this paper was that cirrus cloudiness had increased in coverage and occurrence in the main air-traffic flight corridors. However, it was acknowledged that other causes could be contributory in a multi-component way. Extending analyses of possible cirrus cloud increases, IPCC (1999, Chapter 3) concluded that “...*a possible relationship between air traffic and cirrus formation*” may exist (bullet in Executive Summary of Chapter 3).
- 3.5.3.11 At best, the evidence for a causal relationship between increases in air traffic and cirrus coverage is circumstantial.
- 3.5.3.12 The weakest link in the hypothesis of aviation being the cause of trends in cirrus is the historical and present-day quantification of contrail coverage. If the historical contrail coverage could be better quantified, preferably by satellite imagery, along with cirrus coverage in different air traffic density regions, the relationship would be put on a sounder footing.

3.6 “Are the approaches and global databases for estimating radiative forcing adequate?”

Summary

- The databases and approaches for calculating global contrail coverage should be and can be improved. Given that such contrail coverage estimates are foundational to RF calculations, this is a high priority.
- The principal uncertainties in calculating contrail coverage have been identified and include: the normalisation process on limited observations; the simplifications of the air traffic movements and use of fuel consumption as a proxy for movements; the lack of a consideration of diurnal variability.
- Moreover, current estimates are only available for scenarios to 2050—this should be extended to 2100. The bases of the scenarios were IS92a/e/f—new scenarios should be constructed under SRES assumptions.
- Commensurate improvements in meteorological models in predicting water vapour, temperature and cirrus cloud coverage would be advantageous. However, this requires a large input from the meteorology community.

3.6.1 Estimating global contrail coverage

3.6.1.1 In order to estimate RF by contrails on a global basis it is necessary to know where and when contrails are produced in order to calculate the resultant RF. Sausen *et al.* (1998) have presented a methodology for calculating contrail coverage from 1992 air traffic that was extended to a 2050 scenario by Gierens *et al.* (1999), both of DLR. Sausen *et al.* (1998) estimated the global distribution of contrail formation potential and then the contrail coverage using European Centre for Medium Range Weather Forecasting (ECMWF) re-analysis data and an aircraft fuel inventory (see Figure 3-8). Firstly, the approach will be considered in the context of uncertainties and secondly, how it might be improved.

3.6.2 The DLR methodologies for estimating contrail coverage for 1992 and 2015/2050

3.6.2.1 As has been noted, the prediction of contrail formation does not require knowledge of the micro-physics of contrail formation as most methods are empirical. The approach of Sausen *et al.* (1998) entailed the following steps:

1. estimate the potential contrail coverage using the ECMWF re-analysis data of temperature and humidity fields and the Schmidt-Appleman criterion;
2. estimate the actual contrail coverage using the global distribution of annual mean air traffic from an inventory of fuel consumption by aircraft as a proxy;
3. use of the estimate of mean contrail coverage over Europe/N Atlantic using AVHRR data (Bakan *et al.* 1994) to normalise the results.

3.6.2.2 For the 2050 scenario, Gierens *et al.* (1999) used the same procedure as above but combining ECMWF data with a 2050 aviation scenario of fuel usage. In addition, the expected overall increase in propulsion efficiency of aircraft was accounted for.

3.6.2.3 There are several sources of uncertainty in these estimations: namely, the contrail formation criterion, the ECMWF re-analysis data, the air traffic input data, the temporal resolution, and the normalisation process.

UNCLASSIFIED

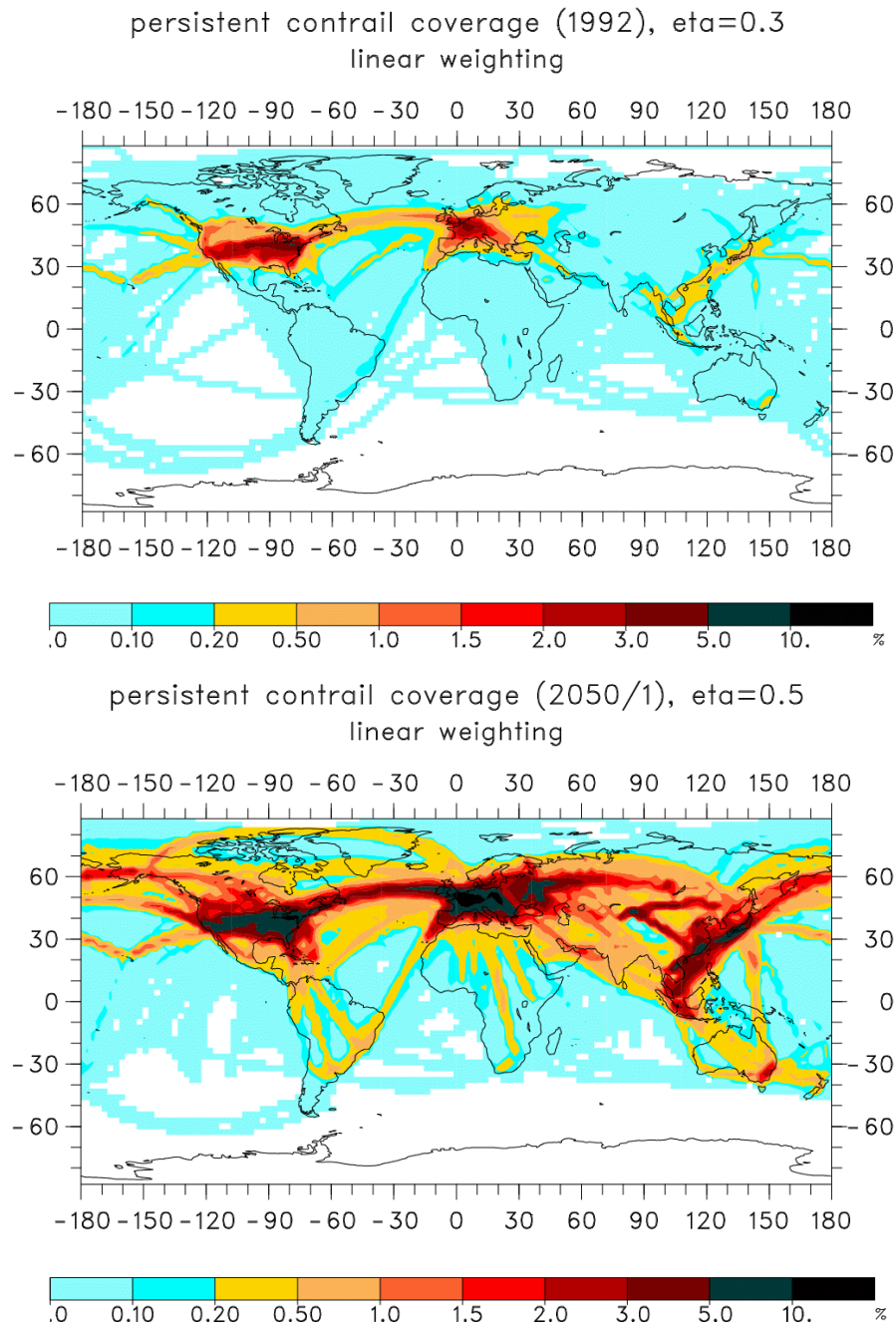


Figure 3-8 Persistent contrail coverage for 1992 (upper panel) from Sausen et al. (1998) and 2050 under Fa1 scenario (lower panel) from Gierens et al. (1999)

3.6.2.4 These sources of uncertainty are dealt with in turn below.

- **Contrail formation criterion.** As discussed previously, little uncertainty remains in the modified Schmidt/Appleman criterion as it is based upon many data that fit the thermodynamic theory quite well. It has the advantage of being empirical and does not require any knowledge of contrail microphysics and chemistry.
- **The ECMWF re-analysis data.** The results depend upon the accuracy of the temperature and humidity data of ECMWF. The ECMWF data are from an initialised GCM rather than measurements for the upper troposphere. Cirrus prediction in GCMs is notoriously difficult—overall, Sausen *et al.* (1998) considered this to be a less serious uncertainty as the contrail parameterisation uses the humidity that remains after cirrus formation and that never exceeds ice supersaturation. However, it was speculated that varying degrees of underestimation of potential contrail cloudiness may impact the spatial contrail distribution.
- **The air traffic input data.** These data are taken from a global 3D inventory of fuel and NO_x emissions, utilising the fuel usage per grid cell as a proxy for number of movements per grid cell. Gierens *et al.* (1999) tested this simplification with a limited data set of movements rather than fuel usage and found a smaller overall coverage of contrails globally, by 10%, but larger differences regionally: 15% more cover in the US and a factor of 2 less over South-East Asia. The inventory used assumes great circle distances and does not account for real movements that can deviate substantially from idealised routing. Moreover, and perhaps more serious, the movements assume optimal profiles flown by the aircraft for fuel usage which is certainly not the case in heavily trafficked areas such as Europe and North America. The actual movements database has its own inherent uncertainties but these are not likely to be large in comparison to other factors and were considered by Gardner *et al.* (1997; 1999). A further point of relevance for future assessments is the base-year of the database: given that air traffic has a rather high growth rate, 1992 movements are certainly not representative of present-day values. In summary, the largest uncertainties in the air traffic input data to Sausen *et al.*'s assessment is the use of fuel as a proxy for movements and the optimised profiles.
- **Temporal resolution.** Temporal resolution is discussed by Sausen *et al.* in the context of the ECMWF data, finding a pronounced annual cycle. However, diurnal cycles which may be important in terms of the air traffic and the temperature and humidities are likely to be rather important. Gierens *et al.* (1999) briefly mention diurnal variability within the original Bakan *et al.* (1994) observations of contrail coverage but not air traffic. This is an important (currently undetermined) parameter in annual aircraft movements as RF at the top of the atmosphere (TOA) is positive and strongest at night and negative during the day at the surface (Meerkötter *et al.*, 1999).

3.6.3 Improving the input data

3.6.3.1 Several aspects of the DLR methodology could be improved given commensurate improvements in the input data. Of the input data and assumptions, the most critical are the air traffic data as a proxy for movements and the normalisation to central European observed contrail coverage.

3.6.3.2 In order to improve the air traffic data and assumptions the following are required as an ideal:

- a. an updated base year for air traffic movements;
- b. a better representation of horizontal (routes) and vertical (profiles) movements;
- c. a measure of movements rather than utilising fuel as a proxy;
- d. data that account for diurnal movements;
- e. updated scenarios which account for the above, consistent with the new IPCC SRES scenarios and compiled for 2100 as well as 2050.

UNCLASSIFIED

- 3.6.3.3 The outlook for obtaining the above is quite good. Some of these requirements will be provided from work being undertaken at DERA at the moment and others from another piece of work—AERO2K—a European Commission Fifth Framework Programme⁴ research project.
- 3.6.3.4 The other crucial improvement would be to obtain more observational data with which the DLR approach can be calibrated and validated. Both up-to-date observations and coverage of areas in addition to central Europe are vital, assuming improvement of the DLR approach rather than development of other approaches.
- 3.6.3.5 There is some recent additional evidence that the situation with observed contrails and air traffic movements needs much improvement: Meyer (2000; Meyer *et al.*, 2000) found a rather poor correlation (0.27) between observed contrail coverage over western Europe and the distribution of fuel consumed according to the ANCAT/EC2 inventory (Gardner *et al.*, 1998) at flight levels between 10–12 km. It is speculated here that some of the differences may have arisen from the observations being inconsistent in time with the inventory but, perhaps more importantly, the idealised nature of the inventory database is a significant weakness in estimating contrail coverage.
- 3.6.3.6 In future predictions of contrail coverage and radiative forcing, the approach thus far has been to use the ECMWF reanalysis data (Minnis *et al.*, 1999; Gierens *et al.*, 1999). It would be more satisfactory to use modelled ice supersaturation from GCMs in atmospheres that account for climate change. Unfortunately, GCMs are rather poor at such predictions. Accurate predictions of the atmospheric impact depends upon how reliably meteorological models can predict regions in the atmosphere prone to contrail formation.
- 3.6.3.7 Moreover, future research needs to be committed to improving the predictive capability of large-scale models in terms of a better representation of the location of the tropopause, water vapour and temperature fields⁵ and cirrus clouds.

⁴ DERA is the co-ordinator (first author of this report).

⁵ Note that already observed changes of water vapour mixing ratios and temperatures in the lower stratosphere caused by the greenhouse effect is a climate change issue. Water vapour molecules are precursors of hydrogen oxide (HO_x) radicals. Increasing HO_x levels and decreasing temperatures enhance ozone depletion in the lower stratosphere. Over the period 1980–1996, ozone declined with a trend of about 7.5 +/- 5 % per decade at an altitude of 15 km at northern midlatitudes (SPARC, 1998).

3.7 “Is it possible to determine radiative forcing from measurements of radiation balance anomalies?”

Summary

- It does not appear practicable to directly link persistent radiation balance anomaly measurements to the flights of individual aircraft with our current and near future satellite data and technologies.
- However, the pattern of air traffic movements over the North Atlantic is sufficiently structured to allow correlations with radiation balance anomalies to be constructed, enabling the uncertainties in RF to be significantly reduced.

3.7.1 The current situation

3.7.1.1 The current method of estimating persistent contrail coverage (Sausen *et al.*, 1998) was reviewed in Section 3.6. This potential coverage is then used to derive the global distribution of annual and daily mean net instantaneous radiative forcing (Minnis *et al.*, 1999). This method relies on observations to calibrate a model.

3.7.1.2 This section deals with the question as to whether an alternative observation-based approach is possible.

3.7.2 A potential advanced satellite-based approach

3.7.2.1 Meerkötter *et al.* (1999) calculated the TOA flux change as a function of the optical depth at 0.55 μm . This function is zero at zero optical depth and is a linearly increasing function of optical depth for small values. The rate of change of flux change with optical depth decreases thereafter so that there is a maximum flux change at an optical depth of about 2.5.

3.7.2.2 Betancor-Gothe and Grassl (1993) calculated the brightness temperature difference between AVHRR channels 4 and 5 as a function of the optical depth at 0.55 μm . It will be recalled that this temperature difference is used, among other considerations, to identify contrails from satellite data. The functional dependence of this temperature difference on optical depth is essentially the same as the TOA flux change, as described above. Thus it can be deduced that TOA flux change is a simple linear function of channel 4/5 temperature difference. It should be noted that the relationship depends upon other parameters such as surface characteristics. However, if it were practicable to measure the temperature difference continuously in space and time, it would be possible to infer the TOA flux change without needing to estimate either the mean contrail coverage or the mean contrail optical depth. As will be seen in Appendix A1, from MSG⁶ data it appears that it is not possible to make this measurement with sufficient signal-to-noise.

3.7.3 Direct measurement of radiation balance anomaly

3.7.3.1 In order to minimise the uncertainty in the radiative forcing using a measurements-based approach, a global, satellite-based monitoring system that would also assimilate aircraft movement data would be needed. This would then enable aircraft fuel consumption and RF to be related both locally and globally.

⁶ MSG = METEOSAT Second Generation, GERB=Geostationary Earth Radiation Budget instrument, on MSG, SEVIRI=Spinning Enhanced Visible and Infrared Imager instrument, also on MSG

UNCLASSIFIED

3.7.3.2 However, the radiative balance depends on three environmental (i.e. aviation independent) parameters:

- surface characteristics;
- atmospheric composition and temperature;
- cloud distribution.

3.7.3.3 Therefore it will always be difficult to uniquely decompose the local measured radiation balance anomaly into the environmental effects and the aviation effects. The best chance of success would come in a geographical area where the variability of aviation activity is high but the variation of the environmental effects are small.

3.7.3.4 The North Atlantic Flight Corridor is such an area. In Appendix A1 it is shown that relating radiation balance anomaly directly to individual aircraft movements, even over the North Atlantic, using MSG data from the Geostationary Earth Radiation Budget (GERB) instrument, will not be practicable because of the signal-to-noise of the GERB instrument. However, it would be possible to relate the diurnal variations of radiation balance anomaly to the diurnal variations of air traffic movements. Thus, it would be possible to derive a relationship between air traffic density and radiation balance anomaly, which can be considered reliable for the North Atlantic area.

3.7.3.5 The variability of the annual mean potential coverage of contrails, as computed by Sausen *et al.* (1998), is dominated by dependencies on latitude and altitude – longitudinal variability is small in comparison. Therefore, if the dependency of mean contrail coverage on air traffic density could be established for the North Atlantic Flight Corridor, say between 30° N and 60° N, then this could be applied with a high degree of confidence to other parts of the world in that latitude band. This assumes that the dependency relationship will be a function of latitude, altitude and time of year. A very high percentage of air traffic is to be found in this latitude band – the only part of the world not in this band where there is significant air traffic is the SE Asia/NE Pacific Rim area. Thus, the uncertainty in the global RF could be reduced significantly by a study of the North Atlantic region, provided there are reliable data for air traffic movements in other parts of the world.

3.7.3.6 In the following sections, 3 approaches are described by which uncertainties may be reduced.

3.7.4 **Approach 1: Reduction of the uncertainty of the current effects of contrails on radiation balance**

3.7.4.1 In this first approach, air traffic movements would be correlated with the associated radiation balance anomaly over the North Atlantic. The diurnal and geographical variability of air traffic over the North Atlantic would give rise to sufficiently large variations in radiation balance anomaly to be detectable in envisaged satellite data. The basis requirements would be:

- **Collection of aircraft position data.** For the defined area of interest, a 4-D representation of each aircraft movement between Europe and North America would be required.
- **Application of advection by the wind.** Significant radiation balance anomalies will only occur if the contrail persists for of the order of an hour or so. During this time it will move downwind by up to a few hundred kilometres so this effect cannot be ignored. It is considered that Numerical Weather Prediction (NWP) model wind data are sufficiently accurate for this purpose. However, this assumes, assuming that:
 - the horizontal resolution of the radiation balance data is 50 km (which is true for GERB data);
 - the timescales involved are of the order of an hour or two.

3.7.4.2 Errors in the NWP data would become significant if the timescales were of the order of a day or so.

3.7.4.3 **Comparison with satellite radiation balance data.** It is assumed that the satellite data concerned are GERB data. These will be available with high time resolution (5 minutes) and approximately 50 km spatial resolution for the area viewed by METEOSAT. The comparison data set will consist of the radiances from the instrument together with the number of aircraft that were in that cell at various times prior to the time of the radiance measurement (taking into account the advection). It is argued that if a sufficiently large sample is taken *and* the effect of contrails on the radiation balance is significant, then the cells having more aircraft will be associated with an average radiation balance anomaly. This will be true even though, on an individual day, a cirrus cloud will form in an area where there have been no aircraft and this cloud will affect the radiation balance significantly. However, this comparison will provide a functional statistic without providing any understanding of the importance of the mechanisms linking the presence of the aircraft to the radiation balance anomaly. This lack of understanding will hamper our ability to predict future effects of contrails on climate.

3.7.5 Approach 2: improving current accuracy in forecasts of contrails, particularly those contrails which have greatest effect on the radiation balance

3.7.5.1 In this approach, predictions of persistent contrails would be made, based on aircraft position data and NWP model parameters which appear relevant and compare the results with AVHRR data. This could be done for any area but again the North Atlantic is attractive, partly because of the relative simplicity of collecting aircraft position data, and also because detecting contrails with AVHRR data is easier and more reliable over ice-free sea than over land. In principle, this exercise could involve running a high-resolution model that would explicitly predict the evolution of the contrail, using boundary and initial conditions from an operational NWP model. However in practice a more sensible approach is to:

- assess the sensitivity of the high resolution model to the boundary and initial conditions. To some extent this has already been done (Gierens, 1996; Jensen *et al.*, 1998b; Chlond, 1998; Boin and Levkov, 1994);
- assess the accuracy, in the NWP model, of those parameters to which the high resolution model appears most sensitive.

3.7.5.2 This option thus involves comparing NWP data, aircraft position data and AVHRR data.

3.7.6 Approach 3: a combination of approaches 1 and 2 with additional cross checking

3.7.6.1 Although approaches 1 and 2 are independent (apart from both relying on aircraft position data), they process data in which there should be significant correlations. In this approach (3), two correlations can be confirmed which would not be addressed by either approach 1 or 2.

3.7.6.2 **The AVHRR and GERB data.** AVHRR can confirm the existence of a contrail, and GERB can detect an instantaneous local (to within 50 km) radiation balance anomaly. Thus by comparing these datasets, a figure for the radiation balance change per unit length of detectable contrail could be derived. Such a figure will be very useful for improving our understanding of the magnitudes of the various factors involved in the connection between contrail formation and radiative forcing.

3.7.6.3 **NWP data and GERB data.** It is expected that, for volumes of the atmosphere where there are aircraft present, the radiation balance anomaly would be greatest where/when the NWP model is predicting conditions under which persistent contrails will form. Confirmation of this would be useful. Also this would give confidence that, if the same NWP model is used to predict the frequency of conditions under which persistent contrails will form in some future epoch, then some confidence can be associated with these predictions.

3.7.7 Note on approach to be adopted in event of failure or delay to GERB

3.7.7.1 The above three approaches critically depend upon the availability of data from the GERB instrument on MSG. There is always an element of risk associated with space technology, particularly where both the instrument and the satellite are untried. An additional risk is that of delay.

3.7.7.2 A fall- back position would be the use of data from the NASA satellites EOS-AM and EOS-PM. EOS-AM (Earth Observation Satellite crossing the equator at 10:30 a.m. each day) was recently renamed Terra and was launched on December 18th 1999. EOS-PM makes its equatorial crossing 4 hours after EOS-AM and is due for launch in December 2000. Both satellites carry both the MODIS and CERES instruments. MODIS (Moderate-Resolution Imaging Spectroradiometer) is a development from AVHRR but with more channels and higher spatial resolution: it therefore will be capable of detecting contrails in the same way as AVHRR can. CERES (Clouds and Earth's Radiant Energy System) is a development from the ERBE (Earth Radiation Budget Experiment) instrument, having the capability of measuring broadband radiances with high absolute accuracy. Thus, these instruments will be capable of providing a snapshot of both contrails and the instantaneously associated radiation balance anomaly. In combination the two satellites will give a picture of sorts of the persistence of the contrails which will reduce the uncertainties, but not by as much as GERB will.

3.8 “How good is the representation of contrails/cirrus for estimating radiative forcing and subsequent climate change?”

Summary

- Further developments in radiative forcing calculations for contrails are constrained by uncertainties in the input data. The main uncertainties are the contrail coverage and the optical thickness of contrails. Although a first attempt has been made to estimate impacts in a GCM (Ponater *et al.*, 1996) the methodologies for estimating contrail coverage have subsequently been refined.
- The current methodology calculates an instantaneous radiative forcing with no feedbacks, not a climate response.
- A better calculation of radiative forcing from contrails is feasible using an artificially amplified forcing. This would help understand the *climate* response (not merely quantify a global radiative forcing), particularly as there is evidence that the climate may be more sensitive to inhomogeneous forcings (e.g. from aircraft) than forcings from other well-mixed gases. This could be done in parallel with refining contrail coverage input data.

3.8.1 Radiation flux calculations for persistent contrails and cirrus clouds

- 3.8.1.1 As is the case for cirrus clouds, the presence of persistent contrails has been calculated to result in a positive global annual mean net RF as the positive terrestrial RF is stronger than the negative solar RF.
- 3.8.1.2 Minnis *et al.* (1999) used a detailed radiative transfer code to estimate the 1992 global mean RF of contrails to be $+0.02 \text{ W m}^{-2}$ with an uncertainty of approximately a factor of 4, yielding a range of approximately $+0.005 \text{ W m}^{-2}$ to $+0.08 \text{ W m}^{-2}$. This RF is small compared to the total human-induced RF from greenhouse gas emissions from all sources which is estimated as $+2.35 \text{ W m}^{-2}$ with an uncertainty of 10% (IPCC, 2000).
- 3.8.1.3 In parallel to Minnis *et al.*'s (1999) RF calculations for contrails, Meerkötter *et al.* (1999) conducted a parametric study of the instantaneous radiative impact of contrails using three different radiative transfer models. All three models have been extensively used and tested in other studies. With the exception of the treatment of aspherical particles, the models agreed within 7% for a variety of parameter studies. Under the assumption of a present-day (1992) global mean contrail coverage of 0.1% (Sausen *et al.*, 1998) and an average optical depth of 0.2–0.5, contrails were calculated to result in a annual mean (instantaneous) RF of 0.01–0.03 W m^{-2} , with a best estimate of 0.02 W m^{-2} , equivalent to all previous CO_2 emissions from aviation. The best estimate of 0.02 W m^{-2} was estimated to have an uncertainty of a factor of 5, yielding a maximum range of 0.004–0.1 W m^{-2} . This uncertainty arose from poorly known contrail coverage and optical depth values.
- 3.8.1.4 The global temperature response to such a small radiative perturbation from contrails is unlikely to be detectable in most climate models unless the signal is artificially amplified (see Section 3.8.2). However, in terms of calculating human-induced radiative forcing from specific sources, and thereby targeting emissions reduction priorities, better estimates of the radiative forcing from contrails are required.
- 3.8.1.5 To reduce the uncertainty of the estimates of radiative forcing from those derived by Minnis *et al.* (1999), uncertainties in the spatial and temporal distribution of contrails, uncertainties in the mean contrail optical depth, and uncertainties in the optical parameters associated with contrails need to be addressed. While much effort has been dedicated to *in situ* sampling of cirrus and contrail size distributions and shapes (IPCC, 1999 Chapter 3), measurements of the solar and terrestrial radiative effects of contrails are limited and are confined to surface observations (e.g. Sassen, 1997) or to dated aircraft measurements (e.g. Kuhn, 1970). The only technology appropriate to determine current global effects of contrails is satellite-based. However, in order to predict future effects we need improved understanding of the relationship between microphysical characteristics of contrails and the radiative fluxes.

3.8.1.6 The lack of radiation measurements can only be rectified by employing a suitably well-equipped aircraft measuring within and below persistent contrails. In this way, results from the Edwards and Slingo (1996) two-stream radiative transfer model and the newly developed radiance solver may be validated against the *in situ* radiation measurements. For example, by flying a series of over-passes above a contrail in otherwise cloud-free conditions, the local solar and terrestrial radiative forcing may be measured directly by broad-band instrumentation. The spectral dependence of the radiative forcing may also be measured by high-resolution radiometers and spectrometers. Measurements could be made in a range of contrail stages, from relatively newly formed, to the stage where the contrail has generated a cirrus-like (but contrail generated) cloud. Comparison may then be made against the spectral radiances and irradiances from the Edwards and Slingo (1996) radiation code. This radiation code is currently used in the Hadley Centre Unified GCM, thus any RF calculations performed within the GCM framework would involve the use of a radiation code that has been validated against measurements.

3.8.2 Radiative Forcing from persistent contrails: current methodologies and potential future developments

3.8.2.1 The recent IPCC Special Report (IPCC 1999) and the study by Minnis *et al.* (1999) estimated the RF effect of contrails on climate for present day (1992) and future (2050) scenarios. Minnis *et al.* (1999) used a fairly sophisticated radiation scheme to calculate the RF on a 2.5° latitude \times 2.5° longitude grid, using 40 vertical layers. Input data included atmospheric temperatures and humidities from the National Center for Environmental Prediction (NCEP) re-analyses, surface temperatures and albedos and cloud data from the International Satellite Cloud Climatology Project (ISCCP) and a simple aerosol climatology. The distribution and radiative properties of contrails were added to these background conditions in order to calculate the effect of contrails on the RF at the top of the atmosphere. They resolved the diurnal and annual cycles to produce mean annual distributions of the forcing. Minnis *et al.* concluded that the global mean RF by the current distribution of contrails is about 0.02 Wm^{-2} , rising to about 0.1 Wm^{-2} in 2050. The uncertainty of the 1992 estimate of global RF was a +/- a factor of 4 and that for 2050 by necessity at least the same, if not greater.

3.8.2.2 As described above in Section 3.8.1, Meerkötter *et al.*, (1999) performed similar calculations but explored the sensitivities of different radiation transfer models. The global RF value calculated for 1992 conditions was the same as that of Minnis *et al.* (1999) but with a slightly larger uncertainty range. No estimates were made by Meerkötter *et al.* (1999) for 2050.

3.8.2.3 It is important to consider whether any significant advances on the work of Minnis *et al.* (1999) might be made by the use of a full 3D climate model. Two possible areas could be addressed. Firstly, the climate response, rather than the RF response and secondly, the effects arising from making the calculations under a future climate scenario.

3.8.2.4 A number of studies have been made of the potential regional forcing induced by contrails and were reviewed by the IPCC (1999, Chapter 3). Ponater *et al.* (1996) made a first attempt to simulate the effects of contrails using a GCM and reported a modelled increase in surface temperature in northern mid-latitudes of $>1 \text{ K}$ for an additional cirrus coverage of 5% in the main traffic corridors. Very recently, Rind *et al.* (2000) have presented some GCM-based calculations on contrail RF. Whilst some of the modelling approaches have been developed, the input data have not been improved over that of Minnis *et al.* (1999).

3.8.2.5 Minnis *et al.* (1999) were the first to produce maps of the RF from persistent contrails (see Figure 3-9 below) but did not translate the forcing distribution into a prediction for the subsequent climate change (i.e. the change in surface temperature) as they used a radiative transfer model, not a GCM so it is important to note that these calculations do not include any stratospheric adjustments in temperature. They highlighted the fact that the RF distribution was concentrated in the Northern mid-latitudes and that some concentration of the climate response might be expected in this region. Whether this is indeed the case is a matter for some debate, but it could be addressed with a climate model.

NET CONTRAIL FORCING

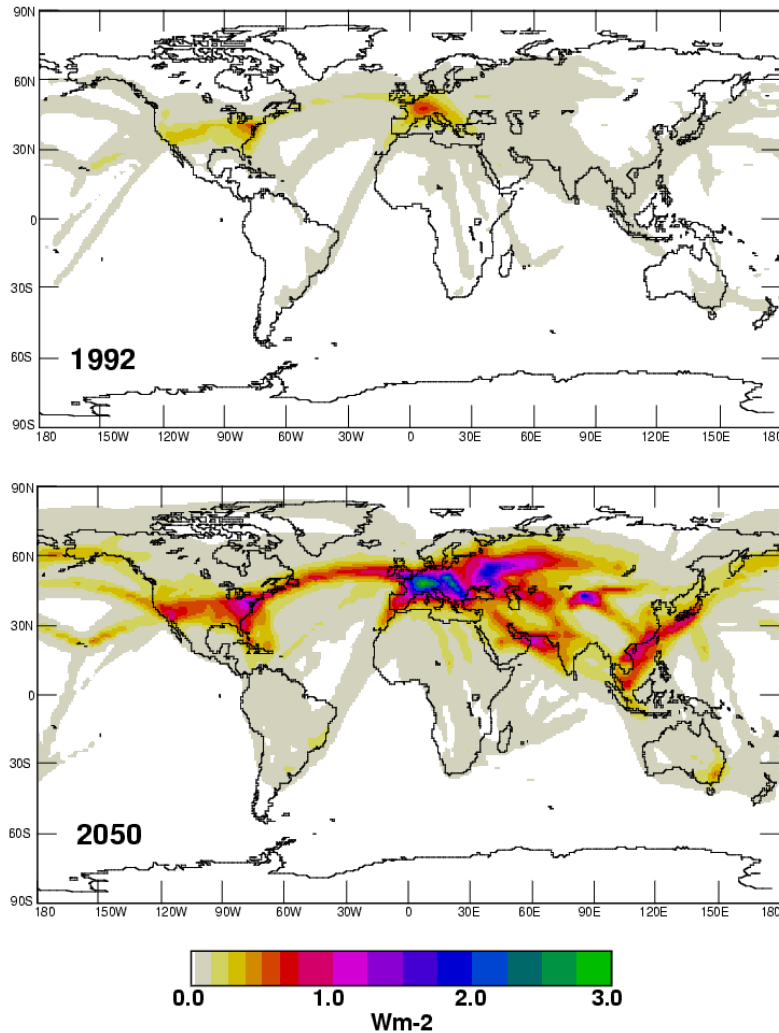


Figure 3-9 Global distribution of radiative forcing from contrails at the top of the atmosphere from 1992 and 2050 aircraft (Minnis *et al.*, 1999).

- 3.8.2.6 The fundamental difficulty with such a calculation is that, even with the 2050 scenario, the RF is extremely small, at least one order of magnitude smaller than that from the rise in well-mixed greenhouse gases. Detecting a measurable signal in the response of a climate model to such a small radiative perturbation would require a large ensemble of integrations to produce an acceptable signal-to-noise ratio. Alternatively, one could force a single simulation with a much larger perturbation with the same pattern, on the assumption that the system is, at least to first order, linear in its response. Ponater *et al.* (1999) and in an extension of this work, Stuber *et al.* (1999) followed such an approach in determining climate response to aircraft O_3 by adding sufficient to produce an adjusted response of $1 W m^{-2}$. The computational investment would still be significant in comparison with that currently used in more conventional climate prediction experiments.
- 3.8.2.7 A parallel problem to that of detecting signal from noise with such small RFs is that the response time by 2050 is rather short. A global mean temperature response based upon the global RF value was calculated by IPCC (1999, Chapter 6) to be an increase of 0.9 K in 2050 over 1990 values based upon the IS92 scenario. Of this 0.9 K, approximately 5% was attributable ($\sim 0.5 K$) to aviation (scenario Fa1). The inadequacy of such time-scales has recently been demonstrated by Sausen and Schumann (1999) for tropospheric O_3 response.

- 3.8.2.8 A potential issue in estimating RF from contrails is the limitations of the concept of RF. The current definition of RF assumes an approximately linear relationship between the global mean RF in $W m^{-2}$ and changes in global mean surface temperatures. Recent work indicates that aviation may produce a different climate signature that is not well represented by an increase in global mean surface temperature (Sausen *et al.*, 1999; Stuber *et al.*, 1999). The basis of this is that the RF produced by aviation is not homogeneous and that the climate sensitivity parameter, λ , where:

$$\Delta T_{surface} = \lambda RF$$

is variable. Ponater *et al.* (1999) found that λ was variable in GCM experiments that used inhomogeneous O_3 perturbations arising from aircraft NO_x emissions. Moreover, the results of these experiments showed that the climate was more sensitive to these O_3 perturbations than perturbations from well mixed greenhouse gases, such as CO_2 . Given that the perturbation of RF from contrails is also non-homogeneous, this gives sufficient justification to make some initial calculations of climate effects in a full 3D GCM.

- 3.8.2.9 The response under future climate conditions is also an issue. By necessity, Minnis *et al.* (1999) assumed that the current distribution of atmospheric temperature, humidity and cloud cover applies both for 1992 and 2050 as they used the NCEP reanalysis data. In reality, these conditions will change in response to global warming and this may affect the calculation for 2050. In particular, the contrail production could be sensitive to the ambient conditions at cruising levels in the upper troposphere and lower stratosphere, where significant warming is expected from climate model simulations (Gierens *et al.*, 1999). Changes in atmospheric and surface temperatures will also affect the greenhouse forcing by the contrails. These aspects could be investigated using a climate model. The negative side of such a study is that the modelled cloud distributions would have to be used and these are one of the weakest aspects of contemporary climate models. By using ISCCP data for 1992, Minnis neatly circumvented this problem, at least for the present day, and it could well be that the assumption that the cloud cover does not change in the next half century is better than relying on an uncertain climate model prediction of future cloud changes.
- 3.8.2.10 Certainly, under a 2050 scenario, the contrail coverage itself should be calculated with a future atmosphere as this was not done by Gierens *et al.* (1999) in their calculation of contrail coverage for 2050 (they did not calculate RF). If a methodology was devised that used a full 3D calculation for 2050, this should be done both with and without the 2050 climate/atmosphere in order to understand the sensitivities and magnitude of responses.

3.9 “What potential is offered by operational measures for reducing contrails?”

Summary

- Flight planning and air traffic management—operational measures—might offer a future role in mitigation of contrail effects. However, there are serious limitations.
- A system to include ‘environmental route planning’ would be complex and would need input from numerical weather prediction models. Currently, the skill with which meteorological models can forecast ‘contrail conditions’ is not of proven quality for such purposes.
- The potential costs of developing and implementing such a system are not justified by current scientific understanding.
- ‘Environmental route planning’ effects need to be understood. There are a number of interactions and tradeoffs that may come into effect. For example, more contrails and (higher water vapour levels) appearing in the lowermost stratosphere may cause chemical perturbations affecting ozone. If lower flight levels were used, increased fuel consumption and CO₂ and NO_x emissions would ensue. These effects have not yet been explored.
- In the broader context of inter-sector measures, it is possible that other proposed policy measures may have adverse environmental effects from contrails: incorporation of aviation into a CO₂ trading regime (under certain plausible assumptions) will increase radiative forcing, not decrease it, and this partly from contrails.

- 3.9.1 The initial formation of contrails for a particular aircraft type flown at a particular altitude is a function of temperature – this is because all the water vapour that condenses to form the initial contrail results from combustion. Thus, contrails will not form unless the temperature is below a threshold value, which is weakly dependent on pressure. However, engine parameters also play a critical role in the formation of contrails as is discussed in Section 3.3.
- 3.9.2 The persistence of contrails depends upon relative humidity. Contrails will not persist if the air is sub-saturated with respect to ice. With respect to existing and potential future supersonic aircraft that fly in the mid-stratosphere, this region will have too low a relative humidity for contrails to persist⁷. Thus, contrails can only form and persist in a layer between the low troposphere (where it is too warm) and the mid-stratosphere (where it is too dry). The height of this layer is a strong function of latitude (being higher in the tropics than middle and high latitudes) and more weakly, a function of time of year (being higher in summer than winter).
- 3.9.3 Tongues of low relative humidity air can connect right down from the stratosphere to the troposphere where it is too warm for contrail formation. Indeed, a useful concept is one of “moist lenses” (Gierens *et al.*, 1997). These are volumes which have a maximum vertical extent of a few kilometres and a maximum horizontal extent of about 1000 km, in which contrails are found preferentially (Bakan *et al.*, 1994). Operational options for contrail reduction are therefore considered to be primarily options for avoiding these moist lenses. An individual lens could, in principle, be avoided by flying over it, under it or around it.
- 3.9.4 In section 10.4.2.1 of the IPCC report there is a discussion of operational measures to reduce emissions. This largely concentrates on measures that will enable aircraft to fly from one airport to another via an efficient route and with minimal delay to all stages of flight, e.g. the ‘great circle distance’ (where favourable meteorological conditions permit) and no stacking of aircraft on approach. Such measures are desirable in terms of reducing fuel usage and subsequent CO₂ emissions.

⁷ However, the importance of additional injection of water vapour into the stratosphere by supersonic aircraft may have some climate implications, depending upon the amount, as discussed in the IPCC report.

UNCLASSIFIED

- 3.9.5 A process known as flight planning determines a provisional route (in 3D) before take-off and clearly this process could include an element intended to reduce the tendency to produce persistent contrails from meteorological forecast data. Whilst such an 'environmental' flight planning process is, in principle, feasible but the quality of meteorological forecasts may be a serious limitation. Our ability to forecast the position (and strength) of the lenses may well be a strongly decreasing function of forecast lead-time, so that such an operational option is likely to change over the flight (depending on the overall mission distance). The latest available data could even include assimilation of data obtained from the aircraft itself, although this would imply a rather complex system.
- 3.9.6 For regions where there is a well defined but variable track structure (e.g. the North Atlantic flight corridor) one could consider adjusting the track structure to reduce contrail formation. Track structure definition is an ATM (Air Traffic Management) activity (as opposed to flight planning, which is an airline activity) and would involve different organisations who would need access to the same meteorological data.
- 3.9.7 An alternative approach to the active 'on-line' process described above would be a more statistical approach, using e.g. something resembling Sausen *et al.*'s (1998) methodology. Such an approach might identify particularly sensitive areas for contrail production requiring some kind of avoidance strategy. However, this would require extensive validation as an approach to mitigation, given the potential expense involved in fuel and ATM demands. Given the dynamics of the atmosphere, it is questionable whether such a statistical approach is of value for mitigation purposes.
- 3.9.8 However, it should be noted that whilst a complex strategy entailing ATM can be envisaged, the overall uncertainties in contrail RF effects are sufficiently large that it is premature to recommend a way forward on operational measures. Moreover, some of the interactions could be complex: flights at higher levels as a first order mitigation option (as noted by IPCC, 1999 Chapter 3) could be beneficial in some areas and detrimental in others.
- 3.9.9 Such complex interactions of latitudinal and altitudinal dependencies of contrail probabilities and trade-offs in terms of fuel burn (and hence CO₂) and NO_x emissions (and hence O₃ formation) need to be explored in considerable detail before operational issues can be considered as 'options'. As yet, there have been no such sensitivity studies although a 5th Framework Program (TRADEOFF) is considering some of these issues. This will report in three years hence, although it is highly likely that the results of individual studies will be reported before this.
- 3.9.10 In the broader context of 'operations', current scenarios being discussed in the policy arena within the scope of the UNFCCC and ICAO may have negative impacts, particularly if market-based options for CO₂ reduction involving simple CO₂ emissions trading are pursued. It is likely that emission trading under the assumptions of open-sector trading, a capped global CO₂ emission, and that aviation is likely, overall, to purchase emission credits, would make aviation impacts worse. This is simply because under these assumptions, contrail production and tropospheric ozone increases will increase RF (Lee and Sausen, 2000).

3.10 “What potential is offered by technological measures for reducing contrails?”

Summary

- Military research has been largely unsuccessful at reducing contrails by technological measures. The most successful strategy has been one of ‘detection–response–avoidance’ by monitoring of the aircraft plume and wake. This is strictly an operational measure but is complicated in its application to the civil fleet as it has implications for air traffic management issues, CO₂ and NO_x production and for operational range.
- No changes in engine technology are envisaged that will dramatically reduce the number of particles from kerosene-fuelled aircraft engines.
- The general trend of increased propulsive efficiency of the aircraft tends towards a cooler exhaust which *increases* the vertical depth over which contrails are produced.
- Reduction in fuel sulphur levels are unlikely to reduce particles sufficiently to make a significant impact on contrail production.
- It is likely that even if particles could be minimised, there are sufficient particles in the background atmosphere to initiate contrail formation. Removal of water from the exhaust is not currently feasible, nor is envisaged to be so in the future.

3.10.1 Minimising contrails—military experiences

- 3.10.1.1 Only a little work has been done on minimising contrails. This has been mostly done in the context of military aviation and as a consequence, much of the material is restricted and/or secret. However, it is clear that such work has met with very little success. The principle approaches have been to colour the contrail, seed the contrail and avoid the contrail.
- 3.10.1.2 Colouring the contrail is feasible but this will only achieve military non-detection objectives. In terms of climate effects, it is possible that colouring will make the contrail optically thicker, thereby *increasing* the climate effect.
- 3.10.1.3 Seeding contrails is not a viable prospect for the civil fleet and has been found to be technically very difficult and not feasible for military aircraft.
- 3.10.1.4 Avoidance of contrails by military aircraft has been another technique adopted by firing a laser beam from the rear of the aircraft to detect when a contrail is being formed. This is perhaps more strictly an operational measure but is included here for consistency with discussing previous military efforts. Whilst this could be made to work (albeit unsatisfactorily for military purposes because of the lag time between detection by the laser and possibility of altitude change by the aircraft) it has the difficulties that this would assume freedom of the aircraft to change flight levels in a real situation. Moreover, the resultant altitude shift (up or down) will have tradeoffs in terms of CO₂ and NO_x emissions. Such aspects have not yet been explored but will be under the previously mentioned TRADEOFF program.

3.10.2 Historical and potential future changes in engine technology

- 3.10.2.1 Through ICAO LTO certification standards, ‘smoke’ levels have been dramatically reduced over the past 20 to 30 years. Aircraft no longer leave a thick plume of smoke on take-off. Given such developments it is a reasonable question as to whether soot (noting the distinction between soot and ‘smoke’ as being operationally defined by measurements) can be further reduced?

- 3.10.2.2 The achievements in smoke reduction have been made by advances in engine combustion and control systems whereby the air and fuel admitted to the combustor is more carefully controlled. In parallel, bypass ratios have steadily been increasing having the effect of greater fuel efficiency, noise reduction and NO_x reduction. However, such technological changes often involve tradeoffs. It is unlikely that bypass ratios can continue to be increased for fuel efficiency as this would imply a hotter core that would ultimately result in the engine producing large amounts of soot.
- 3.10.2.3 In the above, it should also be noted that soot refers to the non-volatile fraction of the particles emitted: as noted before, volatiles are approximately 2 orders of magnitude greater in number density than soot. Smoke is not necessarily equivalent to soot, as smoke is an optically derived measurement from reflectometry measurements of a filter paper.
- 3.10.2.4 As noted in Section 3.3, from the work of Schumann (1996; 2000) and Schumann *et al.* (2000), it has been demonstrated that more modern engines have cooler exhausts and have an increased propensity to produce contrails over older engines. This is a result of an increase in the propulsive efficiency of the aircraft/engine combination, driven by the need to reduce fuel consumption (and as a positive side effect, CO₂).

3.10.3 Changes in fuel composition

- 3.10.3.1 Efforts have been directed to investigating whether the fuel sulphur content affects the contrail-forming propensity of the engine. It has been shown that at normal to very low fuel sulphur levels, that there is no difference. Only when very high fuel sulphur levels are used can a difference be detected (Schumann *et al.*, 1996). In fact, at the very low fuel sulphur levels, almost the same number of particles has been measured giving rise to the hypotheses concerning the roles of chemi-ions and organic compounds in new particle formation. Thus, reducing fuel sulphur levels is not a viable way forward to reduce contrails.

3.10.4 Aircraft particle emissions

- 3.10.4.1 Fundamentally, technological measures amount to whether particles can be minimised in the exhaust of aircraft engines as there is no possibility of removing them mechanically. This, however, ignores the fact that there are usually enough particles in the background atmosphere that would still initiate contrail formation under favourable temperature and humidity conditions. This effect has only been shown in modelling studies but it seems unlikely that minimising particle emissions would have a significant effect on contrail formation. The other essential ingredient is water, for which there is no means of removal.

4 Conclusions

In this section, the approach taken has been to connect the conclusions from the individual summaries to questions posed in Section 3 to the uncertainties in the RF bars given by IPCC (1999), thus categorising how uncertainties might be reduced for '*contrails*' and '*cirrus clouds*' (or rather, aviation-induced cirrus clouds). It is recalled here that a best estimate of RF for current and future aviation for *contrails* was given by IPCC, although the 2/3 uncertainty bars were larger for future aviation; for *cirrus clouds*, no best estimate could be given (see Figure 2.1).

It is clear that there are some overlaps in requirements for reducing the uncertainties for both RF estimates. Moreover, it is clear that some requirements contribute directly to current methodologies for deriving the RFs whereas others increase understanding in a more mechanistic way. This is not to suggest in any way that mechanistic studies are less important, as these facilitate methodological approaches.

4.1 Reducing the uncertainties in estimates of radiative forcing from contrails

4.1.1 Contrail microphysical properties

4.1.2 The relative roles of sulphur, organic compounds and chemi-ions in particle production in the plume are not well understood. This should be resolved. Moreover, the particle production in the engine itself is even more poorly understood: this represents a constraint for any improvement in knowledge of plume processes.

4.1.3 The relative roles of homogeneous and heterogeneous freezing of particles are not well understood. Laboratory studies may help resolve this.

4.1.4 Contrail radiative properties

4.1.5 The way in which contrail-cirrus and natural cirrus clouds differ from each other in radiative properties is not well understood. Direct and remote measurements would improve this situation.

4.1.6 Effects of changes in engine technology

4.1.7 Only one in-flight demonstration of the effect of older vs newer engine technology has been performed. Better quantification of this under a variety of circumstances would improve our understanding of the effect of changes in propulsive efficiency on contrail coverage, and thus RF.

4.1.8 Quantification of contrail coverage through measurements and modelling

4.1.9 The quantification of global and regional contrail coverage from observations is poor. This could be rectified by better utilisation of satellite data. Further efforts could be made on automatic detection of contrails from satellite data that discriminate positive and negative data artefacts better.

4.1.10 Databases and approaches to modelling contrail coverage should be improved. Specifically: air traffic movements, measurements of contrail coverage (see above), optical thicknesses, meteorological input data, quantification of future propulsive efficiencies. The validation of such approaches should be made, including direct measurements of radiation balance anomalies in a heavily trafficked area.

4.1.11 Climate and RF effects of contrails

4.1.12 Climate modelling of contrails should be progressed by incorporating improvements from (4.1.8) into carefully-designed GCM experiments. It is necessary to understand the climate response, not merely RF estimates on regional and global scales.

4.2 Reducing the uncertainties in estimates of radiative forcing from aviation-induced cirrus

4.2.1 The link between aviation and increased cirrus coverage

- 4.2.1.1 There is very poor evidence for a causal link between increases in air traffic and increased cirrus coverage. This should be urgently rectified by further studies utilising satellite and aircraft movements data.
- 4.2.1.2 A better quantification of the optical thickness of contrail–cirrus transitions should be made.
- 4.2.1.3 The potential coverage of contrail-induced cirrus and its radiative properties are unknown. In this respect it is difficult to know whether the microphysical properties of ‘clean’ cirrus are well understood, given the extensive potential impact of aviation on cirrus in the Northern Hemisphere.
- 4.2.1.4 Whether residual particles from short-lived contrails are better cloud condensation nuclei than background particles is unknown. Laboratory studies could help clarify this.
- 4.2.1.5 Databases and approaches to estimating aviation-induced cirrus coverage should be improved. This will allow first ‘best’ estimates of RF.

5 Reducing the uncertainties—research priorities

5.1 Current complimentary work

5.1.1 Much work has been committed to understanding contrail effects. Nevertheless, this is far from complete and this document shows the need for very disparate areas to be considered and pulled together for RF estimates. Individual programmes that will improve our understanding include:

- PARTEMIS—A European Fifth Framework Programme to look at particle formation in the combustor through to the young plume;
- TRADEOFF— A European Fifth Framework Programme to look at the different impacts of aviation with the use of chemical transport and climate models, to see how effects may be minimised;
- INCA— A European Fifth Framework Programme to compare and contrast cirrus properties in the clean Southern Hemisphere and polluted Northern Hemisphere;
- AERO2K— A European Fifth Framework Programme that will construct a global air traffic movements database and subsequent emissions for the year 2001, including a 4D analysis of traffic and parameters required for climate modelling;
- CRYOPLANE— A European Fifth Framework Programme that will scope out the technology and infrastructure required for a hydrogen-powered aircraft, including theoretical climate impacts;
- PAZI—A German national programme on the impacts of contrails, looking at particular at the microphysics and chemistry of contrails.

5.1.2 Of note, is that there are no UK research projects on aviation contrail impacts (other than UK involvement in three of the above-listed projects by DERA and one by the University of Cambridge) other than a study within the UTLS programme that is looking at surface uptake properties on ice and soot (R. A. Cox, University of Cambridge).

5.1.3 Moreover, in terms of current new programs within Europe, **there is no one national or international programme that is directly addressing reducing uncertainties in an integrated approach.** On the wider international scene, the only significant program is that in the United States (NASA) which currently has an uncertain future.

5.2 Research priorities

- 5.2.1 Two approaches are possible. One is to quantify the direct relationship between satellite measurements of radiation balance parameters and aircraft movement data. The other is to improve our knowledge of all the processes that link the presence of an aircraft to the occurrence of a radiation balance anomaly. The first approach would give rise to information on the current relationship but little capability for predicting how that relationship might change in the future. The second approach would lead to greatly increased understanding of the current uncertainties and a strengthening of the weakest links in this long calculation chain.
- 5.2.2 **The first approach**, which potentially relies heavily on the availability of data from the Geostationary Earth Radiation Budget (GERB) instrument of the METEOSAT Second Generation satellite (MSG) to be launched in 2002), would be to measure the radiation balance anomaly associated with contrails in conjunction with air traffic control data. This would reduce the uncertainty in the effects of contrails on the radiation balance. In addition, using such data, the accuracy in forecasts of contrails, particularly those contrails that have greatest effect on the radiation balance, could be measured. This would improve techniques for forecasting contrails.
- 5.2.3 **The second approach** requires 8 steps as follows:
- 5.2.4 All these steps are required. Thus it is not possible to prioritise the below list: they are all required to reduce uncertainties associated with contrail and aviation-induced cirrus RF.
1. Further measurements of contrail coverage from different regions of the globe
 2. Quantitative evidence of the formation of cirrus cloud from aircraft exhaust particles
 3. A better understanding of particle formation including throughout the engine and in the plume
 4. Observations quantifying the differences between 'clean' and aviation-impacted cirrus
 5. An improved aircraft movement database for contrail coverage calculations
 6. A better quantification of the connection between cirrus coverage trends and air traffic
 7. More data on the impact of engine/airframe efficiency on contrail formation.
 8. Incorporation of RF calculations into a GCM framework
- 5.2.5 Of the above requirements, European EU Programmes are in place that will satisfy the needs of Research Priorities 3 (PARTEMIS), 4 (INCA), and 5 (AERO2K). However, efforts on the other research priorities are not as concrete and no overall research programme exists that has the overall aim of reducing uncertainties in the RF effects of contrails and aviation-induced cirrus. This is *the* urgent research requirement.
- 5.2.6 One potential route forward, which heavily relies upon availability of data from the GERB instrument on MSG (to be launched 2002) is to measure the radiation anomaly associated with contrails in conjunction with air traffic control data. This would reduce the uncertainty in the effects of contrails on the radiation balance. In addition, using such data, the accuracy in forecasts of contrails, particularly those contrails that have greatest effect on the radiation balance, could be measured. This would improve techniques for forecasting contrails.

Acknowledgements

We gratefully acknowledge the funding of this study by the Department of the Environment, Transport and the Regions, Global Atmosphere Division under contract EPG 1/1/95 and the encouragement and enthusiasm of Drs Gordon McFadyen and Cathy Johnson. Dr Geoff Jenkins of the Hadley Centre for Climate Prediction and Research played a vital facilitating role and we thank him for his enthusiasm and help. Prof. Ulrich Schumann, Prof. Robert Sausen, Dr Andreas Petzold, Dr Franz Schröder, Dr Klaus Gierens, Dr Michael Ponater, Dr Peter Wendling, Dr Herman Mannstein, Dr Johannes Hendricks and Dr Richard Meyer (DLR, Institute for Atmospheric Physics, Oberpfaffenhofen) are thanked for fruitful and stimulating discussions. We particularly thank Ulrich Schumann and Franz Schröder of DLR for providing copies of manuscripts prior to publication. Many of the graphics are taken from the DLR Institute for Atmospheric Physics picture archive and we acknowledge this source. Also, we gratefully acknowledge Drs Kathy Shah and David Rind (NASA GISS) for providing their manuscript prior to publication.

UNCLASSIFIED

UNCLASSIFIED

6 References

- Anderson B. E., Cofer W. R., Barrick J. W., Bagwell D. R., Hudgins C. H. and Nowicki G. D. (1998a) Airborne observations of aircraft aerosol emissions. 1. Total and nonvolatile particle emission indices. *Geophysical Research Letters* **25**, 1689–1692.
- Anderson B. E., Cofer W. R., Bagwell D. R., Barrick J. W., Hudgins C. H. and Brunke K. E. (1998b) Airborne observations of aircraft aerosol emissions. 2. Factors controlling volatile particle production. *Geophysical Research Letters* **25**, 1693–1696.
- Anderson B. E., Cofer W. R., Gregory G. L., Vay S., Brunke K. E., Kondo Y., Koike M., Chlager H., Baughcum S. and Jensen E. J. (1999) An assessment of aircraft as a source of particles to the upper troposphere. *Geophysical Research Letters* **26**, 3069–3072.
- Appleman H. (1953) The formation of exhaust condensation trails by jet aircraft. *Bulletin of the American Meteorological Society* **34**, 14–20.
- 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.
- Arnold F., Stimp Th., Busen R. and Schumann U. (1998) Jet engine exhaust chemi-ion measurements: implications for gaseous SO₃ and H₂SO₄. *Atmospheric Environment* **32**, 3073–3077.
- Bakan S., Betancor-Gothe M., Gayler V. and Grassl H. (1994) Contrail frequency over Europe from NOAA-satellite images. *Annales Geophysicae* **12**, 962–968.
- Betancor-Gothe M. and Grassl H. (1993) Satellite remote sensing of the optical depth and mean crystal size of thin cirrus and contrails. *Theoretical and Applied Climatology* **48**, 101–113.
- Boin M. and Levkov L. (1994) A numerical study of contrail development. *Annales Geophysicae* **12**, 969–978.
- Borrmann S., Solomon S., Dye J. E. and Luo B. (1996) The potential of cirrus clouds for heterogeneous chlorine activation. *Geophysical Research Letters* **23**, 2133–2136.
- Boucher O. (1999) Air traffic may increase cirrus cloudiness. *Nature* **397**, 30–31.
- 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.
- Cannon R. H. (1971) Planning a program for assessing the probability that SST aircraft might modify climate (SST operation, climatic impact assessment program, considering carbon dioxide, water vapour, contrails, particulates, nitrogen oxides and carbon monoxide). *Bulletin of the American Meteorological Society* **52**, 836–842.
- 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.
- Chlond A. (1998) Large-eddy simulation of contrails. *Journal of the Atmospheric Sciences* **55**, 796–8190
- Crutzen P. J. (1971) Ozone production rate in an oxygen-hydrogen-nitrogen atmosphere. *J. geophys. Res.* **76**, 7311–7327.
- 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.
- DeMott P. J., Rogers D. C., Kreidenweis S. M., Chen Y., Twohy C. H., Baumgardner D., Heymsfield A. J. and Chan K. R. (1998) The role of heterogeneous freezing nucleation in upper tropospheric clouds: inferences from SUCCESS. *Geophysical Research Letters* **25**, 1387–1390.
- DeMott P. J., Chen Y., Kreidenweis S. M., Rogers D. C. and Sherman D. E. (1999) Ice formation by black carbon particles. *Geophysical Research Letters* **26**, 2429–2432.
- Derwent R. G. (1982) Two-dimensional model studies of the impact of aircraft exhaust emissions on tropospheric ozone. *Atmospheric Environment* **16**, 1997–2007.
- Diehl J. and Mitra S. K. (1998) A laboratory study of the effects of a kerosene burner exhaust on ice nucleation and the evaporation rate of ice crystals. *Atmospheric Environment* **32**, 3145–3151.

- Döpelheuer A. (1997) Berechnung der Produkte unvollständiger Verbrennung aus Luftfahrtriebwerken. IB-325-09-97, Deutsche Zentrum für Luft- und Raumfahrt, Köln.
- Edwards J. M. and Slingo A. (1996) Studies with a flexible new radiation code I: choosing a configuration for a large-scale model. *Quarterly Journal of the Royal Meteorological Society* **122**, 689–719.
- Ferris P. (1996) The formation and forecasting of condensation trails behind modern aircraft. *Meteorological Applications* **3**, 301–306.
- Gardner R. M., Adams K., Cook T., Ernedal S., Falk R., Fleuti E., Herms E., Johnson C. E., Lecht M., Lee D. S., Leech M., Lister D., Massé B., Metcalfe M., Newton P., Schmitt A., Vandenberg C. and van Drimmelen R. (1997) The ANCAT/EC global inventory of NO_x emissions from aircraft. *Atmospheric Environment* **31**, 1751–1766.
- Gardner R. M., Adams J. K., Cook T., Lason 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., ten Have H., Vandenberg C. (1998) ANCAT/EC2 Global Aircraft Emission Inventories for 1991/92 and 2015. Report by the ECAC/ANCAT and EC working group. DERA, Farnborough, Hants.
- Gayet J. –F., Auroil F., Oschepkov S., Schröder F., Duroure C., Febvre G., Fournol J. –F., Crépel O., Personne P. and Daugereon D. (1998) In situ measurements of the scattering phase function of stratocumulus, contrails and cirrus. *Geophysical Research Letters* **25**, 971–974.
- Gierens K. and Jensen E. (1998) A numerical study of the contrail-to-cirrus transition. *Geophysical Research Letters* **25**, 4341–4344.
- Gierens K. and Schumann U. (1996) Colors of contrails from fuels with different sulfur contents. *Journal of Geophysical Research* **101**, 16731–16736.
- Gierens K. and Ström J. (1998) A numerical study of aircraft wake induced cloud formation. *Journal of the Atmospheric Sciences* **55**, 3253–3263.
- Gierens K., Schumann U., Smit H. G. J., Helten M. and Zangl G. (1997) Determination of humidity and temperature fluctuations based on MOZAIC data and parameterisation of persistent contrail coverage for general circulation models. *Annales Geophysicae* **15**, 1057–1066.
- 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.
- Hagen D. E., Trueblood M. B., and Whitefield P. D. (1992) A field sampling of jet exhaust aerosols. *Particle Science and Technology* **10**, 53–63.
- Hendricks J., Lippert E., Petry H. and Ebel A. (1999) Heterogeneous reactions on and in sulfate aerosols: implications for the chemistry of the midlatitude tropopause region. *Journal of Geophysical Research* **104**, 5531–5550.
- Hendricks J., Lippert E., Petry H. and Ebel A. (2000) Implications of subsonic aircraft NO_x emissions for the chemistry of the lowermost stratosphere: model studies on the role of bromine. *Journal of Geophysical Research* **105**, 6745–6759.
- Heymsfield A. J., Lawson R. P. and Sachse G. W. (1998) Growth of ice crystals in a precipitating contrail. *Geophysical Research Letters* **25**, 1335–1338.
- Hidalgo H. and Crutzen P. J. (1977) The tropospheric and stratospheric composition perturbed by NO_x emissions of high-altitude aircraft. *Journal of Geophysical Research* **82**, 5833–5866.
- 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.
- IPCC SPM (1999) *Aviation and the Global Atmosphere. Summary for Policymakers*. 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, Geneva.
- Jäger H., Freudenthaler V. and Homburg F. (1998) Remote sensing of optical depth of aerosols and clouds related to air traffic. *Atmospheric Environment* **32**, 2123–3127.
- Jensen E. J. and Toon O. B. (1997) The potential impacts of soot particles from aircraft exhaust on cirrus clouds. *Geophysical Research Letters* **24**, 249–252.

UNCLASSIFIED

- Jensen E. J., Toon O. B., Pueschel R. F., Goodman J., Sachse G. W., Anderson B. E., Chan K. R., Baumgardner D. and Miake-Lye R. C. (1998a) Ice crystal nucleation and growth in contrails forming at low ambient temperatures. *Geophysical Research Letters* **25**, 1371–1374.
- Jensen E. J., Ackerman A. S., Stevens D. E., Toon O. B. and Minnis P. (1998b) Spreading and growth of contrails in a sheared environment. *Journal of Geophysical Research* **103**, 31557–31567.
- Johnston H. S. (1971) Reduction of stratospheric ozone by nitrogen dioxide catalysts from supersonic transport exhaust. *Science* **173**, 517–522.
- Joseph E. and Wang W. C. (1999) An interactive cirrus cloud radiative parameterization for global climate models. *Journal of Geophysical Research* **104**, 9501–9515.
- Kärcher B. (1998a) Physico-chemistry of aircraft-generated liquid aerosols, soot, and ice particles. 1. Model description. *Journal of Geophysical Research* **103**, 17111–17128.
- Kärcher B. (1998b) On the potential importance of sulfur-induced activation of soot particles in nascent jet aircraft exhaust plumes. *Atmospheric Research* **46**, 293–305.
- Kärcher B. (1999) Aviation-produced aerosols and contrails. *Surveys in Geophysics* **20**, 113–167.
- Kärcher B. and Meilinger S. (1998) Perturbation of the aerosol layer by aviation-produced aerosols: a parametrization of plume processes. *Geophysical Research Letters* **25**, 4465–4468.
- Kärcher B., Peter Th. and Ottmann R. (1995) Contrail formation: homogeneous nucleation of H₂SO₄/H₂O droplets. *Geophysical Research Research Letters* **22**, 1501–1504.
- Kärcher B., Hirschberg M. M. and Fabian P. (1996) Small-scale chemical evolution of aircraft exhaust species at cruising altitude. *Journal of Geophysical Research* **101**, 15169–15190.
- Kärcher B., Busen R., Petzold A., Schröder F. P., Schumann U. and Jensen E. J. (1998a) Physico-chemistry of aircraft-generated liquid aerosols, soot and ice particles. 2 Comparison with observations and sensitivity studies. *Journal of Geophysical Research* **103**, 17129–17147.
- Kärcher B., Yu. F., Schröder F. P. and Turco R. P. (1998b) Ultrafine aerosol particles in aircraft plumes: analysis of growth mechanisms. *Geophysical Research Letters* **25**, 2793–2796.
- Kästner M., Meyer R. and Wendling P. (1999) Influence of weather conditions on the distribution of persistent contrails. *Meteorological Applications* **6**, 261–272.
- Kästner M., Kriebel K. T., Meerkötter R., Renger W., Ruppertsberg G. H. and Wendling P. (1993) Comparison of cirrus height and optical depth derived from satellite and aircraft measurements. *Monthly Weather Review* **121**, 2708–2717.
- Koop Th, Ng H. P., Molina L. T. and Molina M. J. (1998) A new optical technique to study aerosol phase transitions: the nucleation of ice from H₂SO₄ aerosols. *Journal of Physical Chemistry* **A102**, 8924–8931.
- Kuhn P. M. (1970) Airborne observations of contrail effects on the thermal radiation budget. *Journal of Atmospheric Science* **27**, 937–942.
- Lawson R. P., Heymsfield A. J., Aulenbach S. M. and Jensen E. L. (1998) Shapes, sizes and light scattering properties of ice crystals in cirrus and a persistent contrail during SUCCESS. *Geophysical Research Letters* **25**, 1331–1334.
- Lee D. S. and Sausen R. (2000) Assessing the real impact of CO₂ emissions trading by the aviation industry. *Atmospheric Environment* **34**, 5337–5338.
- Liou K. N. (1986) Influence of cirrus clouds on weather and climate processes: a global perspective. *Monthly Weather Review* **114**, 1167–1199.
- Liou K. N., Yang P., Takano Y., Sassen K., Charlock T. and Arnott W. (1998) On the radiative properties of contrail cirrus. *Geophysical Research Letters* **25**, 1161–1164.
- 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.
- Lyzenga D. R. (1972) Model calculations of contrail effects on the radiation budget. Conference on Atmospheric Radiation, Fort Collins, Colorado, August 7–9th, 1972. American Meteorological Society.
- Lyzenga D. R. (1973) Environmental effects of aircraft condensation trails (on earth surface temperatures). PhD thesis, University of Michigan, Ann Arbor.
- Marquart S., Sausen R., Ponater M. and Grewe V. (2000) Estimate of the climate impact of cryoplanes. DLR Institut für Physik der Atmosphäre Report no. 129, Oberpfaffenhofen.

DERA/AS/PTD/CR000103

UNCLASSIFIED

- Mannstein H., Meyer R. and Wendling P. (1999) Operational detection of contrails from NOAA-AVHRR data. *International Journal of Remote Sensing* **20**, 1641–1660.
- Meerkötter R., Schumann U., Doelling D. R., Minnis P., Nakajima T. and Tsuchimya Y. (1999) Radiative forcing by contrails. *Annales Geophysicae* **17**, 1080–1094.
- Meyer R. (2000) Regionale Kondensstreifen-Bedeckung aus Satellitendaten und ihr Einfluss auf den Strahlungshaushalt. PhD Dissertation der Fakultät für Physik der Ludwig-Maximilians-Universität München, submitted.
- Minnis P., Kratz D., Coakley J., King M., Arduini R., Garber D., Heck W., Mayor S., Smith W. and Young D. (1995) Cloud optical property retrieval (subsystem 4.3), *Clouds and the Earth's radiant energy system (CERES) algorithm theoretical basis document*, Vol III: Cloud analyses and radiance inversions (subsystem 4), NASA Ref paper RP-1376 Vol 3, pp 135–176.
- Minnis P., Ayers K., Weaver S. (1997) Surface-based observations of contrail occurrence frequency over the US April 1993–1994, NASA Reference Publication 1404, Hampton, Virginia.
- Minnis P., Young D., Garber D., Nguyen L., Smith W., Palikonda R. (1998) Transformation of contrails into cirrus during SUCCESS. *Geophysical Research Letters* **25**, 1157–1160.
- 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.
- Minnis P., Palikonda R., Ayers J. K., Duda D. P. and Costulis P. K. (2000) Cirrus, contrails, and radiative forcing over the USA: their relationships to air traffic and upper tropospheric conditions. Presented at 'Aviation, Aerosols, Contrails and Cirrus Clouds (A²C³)' AERONET/CORSAIRE European Workshop, 10th–12th July, Seeheim, Germany.
- Meyer R., Mannstein H., Meerkötter R. and Wendling P. (2000) Regional coverage of contrails derived from satellite data and their radiative forcing. Presented at '25th General Assembly of the European Geophysical Society, Nice, France, April 2000'.
- Paladino J., Whitefield P., Hagen D., Hopkins A. R. and Trueblood M. (1998) Particle concentrations characterization for jet engine emissions under cruise conditions. *Geophysical Research Letters* **25**, 1697–1700.
- Palikonda R., Minnis P., Nguyen L., Garber D., Smith W. and Young D., (1996) Remote sensing of contrails and aircraft altered cirrus clouds. In 'Proceedings of Impact of aircraft emissions upon the atmosphere international colloquium Vol. II', Paris, France, October 15–18 1996, pp439–444.
- Petzold A. and Schröder F. P. (1998) Jet engine exhaust aerosol characterization. *Aerosol Science and Technology* **28**, 62–76.
- Petzold A., Busen R., Schröder F. P., Baumann R., Kuhn M., Ström J., Hagen D. E., Whitefield P. D., Baumgardner D., Arnold F., Borrmann S. and Schumann U. (1997) Near field measurements on contrail properties from fuels with different sulfur content. *Journal of Geophysical Research* **102**, 29867–29881.
- Petzold A., Ström J., Ohlsson S. and Schröder F. (1998) Elemental composition and morphology of ice crystal residual particles in cirrus clouds and contrails. *Atmospheric Research* **49**, 21–34.
- Petzold A., Ström J., Schröder F. P. and Kärcher B. (1999a) Carbonaceous aerosol in jet engine exhaust: emission characteristics and implications for heterogeneous chemistry. *Atmospheric Environment* **33**, 2689–2698.
- Petzold A., Döpelheuer A., Brock C. A. and Schröder F. P. (1999b) In situ observations and model calculations of black carbon emission by aircraft at cruise altitude. *Journal of Geophysical Research* **104**, 22171–22181.
- Ponater M., Brinkop S., Sausen R. and Schumann U. (1996) Simulating the global atmospheric response to aircraft water vapour emissions and contrails: a first approach using a GCM. *Annales Geophysicae* **14**, 941–960.
- Ponater M., Sausen R., Feneberg B. and Roeckner E. (1999) Climate effects of ozone changes caused by present and future air traffic. *Climate Dynamics* **15**, 631–642.
- Rind D., Lonergan P. and Shah K. (2000) Modeled impact of cirrus cloud increases along aircraft flight paths. *Journal of Geophysical Research* **105**, 19927–19940.
- Sassen K. (1997) Contrail-cirrus and their potential for regional climate change. *Bulletin of the American Meteorological Society* **78**, 1885–1903.

UNCLASSIFIED

- Sausen R. and Schumann U. (1999) Estimates of the climate response to aircraft CO₂ and NO_x emissions scenarios. *Climatic Change* **44**, 27–58.
- 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.
- Sausen R., Ponater M. and Stuber N. (1999) Is the climate more sensitive for radiative forcings from aircraft than to other radiative forcings? Presented at Conference on the Atmospheric Effects of Aviation, Virginia Beach, USA, 19th–22nd April, 1999.
- Schmidt E. (1941) Die Entstehung von Eisnebel aus den Auspuffgasen von Flugmotoren—Schriften der Deutschen Akademie der Luftfahrtforschung, Verlag R. Oldenbourg München and Berlin.
- Schröder F., 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.
- Schröder F., Brock C. A., Baumann R., Petzold A., Busen R., Schulte P. and Fiebig M. (2000a) In-situ studies on volatile jet exhaust particle emissions—impacts of fuel sulphur content and environmental conditions on nuclei aerosols. *Journal of Geophysical Research* **105**, 19941–19954.
- Schröder F., Kärcher B., Duroure C., Ström J., Petzold A., Gayet J. –F., Strauss B., Wendling P. and Borrmann S. (2000b) On the transition of contrails into cirrus clouds. *Journal of Atmospheric Sciences* **57**, 464–480.
- Schumann, U. (1990) *Air Traffic and the Environment, Lecture Notes in Engineering*, 60 U. Schumann (ed.), Springer-Verlag, Berlin.
- Schumann U. (ed.) (1995) *The impact of NO_x emissions from aircraft upon the atmosphere at flight altitudes 8–15 km (AERONOX)*. Commission of the European Communities, Brussels.
- Schumann U. (1996) On conditions for contrail formation from aircraft exhausts. *Meteorol. Zeitschrift N.F.* **5**, 4–23.
- Schumann U. (2000a) Influence of propulsion efficiency on contrail formation. *Aerospace Science and Technology* **4**, 391–401.
- Schumann U. (2000b) Contrail cirrus. Institut für Physik der Atmosphäre, Report No. 114, DLR Oberpfaffenhofen, Germany.
- Schumann U., Ström J., Busen R., Baumann R., Gierens K., Krautstrunk M., Schröder F. and Singl J. (1996) In situ observations of particles in jet aircraft exhausts and contrails for different sulfur containing fuels. *Journal of Geophysical Research* **101**, 6853–6869.
- Schumann Y., Chlond A., Ebel A., Kärcher B., Pak H., Schlager H., Schmitt A. and Wendling P. (1997) Pollutants from Air Traffic—Results of Atmospheric Research 1992–1997. Deutsches Zentrum für Luft- und Raumfahrt e.V, Mitteilung 97- 04, Köln
- Schumann U. and Wendling P. (1990) Determination of contrails from satellite data and observational results. *Air traffic and the environment—background, tendencies, and potential global atmospheric effects* U. Schumann (ed.), Springer-Verlag, Heidelberg, pp138–153.
- Schumann U., Busen R. and Plohr M. (2000) Experimental test of the influence of propulsion efficiency on contrail formation. *Journal of Aircraft* (submitted).
- Schmitt and Brunner (1997) Emissions from aviation and their development over time. In ‘Pollutants from Air Traffic—Results of Atmospheric Research 1992–1997’ U. Schumann *et al.* (eds). Deutsches Zentrum für Luft- und Raumfahrt e.V, Mitteilung 97- 04, Köln
- Ström J. and Ohlsson S. (1998) *In situ* measurements of enhanced crystal number densities in cirrus clouds caused by aircraft exhaust. *Journal of Geophysical Research* **103**, 11355–11361.
- Ström J., Strauss B., Anderson T., Schröder F., Heintzenberg J. and Wendling P. (1997) In situ observations of the microphysical properties of young cirrus cloud. *Journal of the Atmospheric Sciences* **54**, 2542–2553.
- Stuber N., Ponater M. and Sausen R. (1999) On the apparent limits of the radiative forcing concept in climate sensitivity experiments related to ozone changes. Presented at the Fourth International Climate Conference, Hamburg, September 1999.
- Sussmann R. and Gierens (1999) Lidar and numerical studies on the different evolution of vortex pair and secondary wake in young contrails. *Journal of Geophysical Research* **104**, 2131–2142.

UNCLASSIFIED

- 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.
- Tremmel H. G., Schlager H., Konopka P., Schulte P., Arnold F., Klemm M. and Droste-Frank B. (1998) Observations and model calculations of jet aircraft exhaust products a cruise altitude and inferred initial OH emission. *Journal of Geophysical Research* **103**, 10803–10816.
- Wyser K. and Ström J. (1998) A possible change in cloud radiative forcing due to aircraft exhaust. *Geophysical Research Letters* **25**, 1673–1676.
- Young D., Minnis P., Baumgardner D. and Gerber H. (1998) Comparison of in situ and satellite-derived cloud properties during SUCCESS. *Geophysical Research Letters* **25**, 1125–1128.
- Yu F. 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.
- Yu F. and Turco R. P. (1998) Contrail formation and impacts on aerosol properties in aircraft plumes: effects of fuel sulfur content. *Geophysical Research Letters* **25**, 313–316.
- Yu F., Turco R. P., and Kärcher B. (1999) The possible role of organics in the formation and evolution of ultrafine aircraft particles. *Journal of Geophysical Research* **104**, 4079–4087.

A Sensitivity of AVHRR, SEVIRI and GERB to contrails and cirrus

| | AVHRR | SEVIRI | GERB |
|--------------------------|----------------------|-------------------------|-------------|
| Satellite | NOAA (polar orbiter) | MSG (geostationary) | MSG |
| Spatial resolution (SSP) | 1 km | 3 km | 48 km |
| Temporal resolution | Twice per day | 15 minutes | 5 minutes |
| Channels | 4 & 5 | 10.8 μ & 12.0 μ | LW and SW |
| Noise | <0.1 K | 0.3 K | 1 Wm^{-2} |

From the above it follows that a contrail which is detectable in AVHRR will not necessarily be detectable in SEVIRI⁸ (particularly bearing in mind that a threshold temperature difference of 0.2 K is used to detect contrails with AVHRR (Mannstein *et al.*, 1999)).

Using Betancor-Gothe and Grassl (1993) for cirrus uncinus cloud for a 0.55 μm optical depth of 0.3 gives a T4-T5 of 1.5 K. If the minimum T4-T5 that can be detected with SEVIRI is 0.5 K (0.3 K is the noise in the individual channels) then the minimum coverage of contrail cirrus that can be detected is 33%.

Using Minnis *et al.* (1999) for cirrus with spherical ice particles, mid-latitude summer continental conditions and a 0.55 μm optical depth of 0.3 gives a radiative forcing of 22 Wm^{-2} . Assuming that the minimum radiation balance anomaly that can be detected by GERB is 1 Wm^{-2} then the minimum coverage of contrail cirrus that can be detected is 4.5%. Although this sounds like better sensitivity than SEVIRI, coverage of 4.5% over a pixel of 48 \times 48 km is, generally speaking, less likely than coverage of 33% over a pixel of 3 \times 3 km. Thus, SEVIRI is more likely to detect a single isolated contrail than GERB (but less likely than AVHRR) but GERB may well detect the combined effects of a number of thin contrails in close proximity (such as may occur in the North Atlantic Flight Corridor). Such increases in size were noted in the SUCCESS project (Toon and Miake-Lye, 1998).

According to Sausen *et al.* (1998) the annual mean contrail coverage in the part of the North Atlantic Flight Corridor having the densest air traffic is 1-1.5% (the underlying methodology assumes a linear dependency of contrail coverage on fuel consumption). The annual mean contrail coverage associated with the North Atlantic Organised Track system is likely to be higher than this because a very high percentage of the traffic uses a very small part of the corridor. According to Meerkotter *et al.* (1999), for North Atlantic summer ocean conditions, and hexagonal ice particles, the net flux change is 31.8 Wm^{-2} for 100% contrail cover. Thus, the flux change for the mean contrail cover is at least 0.318 – 0.477 Wm^{-2} . However, the daily peak air traffic flow in each direction is five times the daily average, so the peak flux change is 1.59-2.38 Wm^{-2} , which is detectable. This peak is based on hourly figures and assuming that a persistent contrail will persist for of the order of one hour, it follows that there will be a peak flux change a few hours after the peak traffic flows in the two directions (for constant atmospheric conditions conducive to contrail persistence).

The link between SEVIRI data and GERB data involves integration over space and spectrum, whilst the impact on radiative forcing relies on integration over time. It has proved possible to track cirrus clouds for periods of several hours using data from current generation METEOSAT. An EU project to exploit GERB data for climate and meteorological applications will quantify the uncertainty in the linkage between GERB data and SEVIRI data.

⁸ Spinning Enhanced Visible and Infrared Imager instrument, also on MSG

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

Distribution list

Dr Gordon McFadyen, DETR, Global Atmosphere Division

Dr David S. Lee, DERA Propulsion and Performance Dept

Mr Phil Clare, DERA Space Department

Dr Jim Haywood, Met. Research Flight, Meteorological Office

Dr Bernd Kärcher, DLR Institut für Physik der Atmosphäre

Mr Bob Lunnon, Meteorological Office

Mr Ian Pilling, DERA Space Department

Dr Tony Slingo, Hadley Centre for Climate Prediction and Research, Meteorological Office

Mr John R. Tilston, DERA Propulsion and Performance Department

Prof. Chris Wilson, DERA Propulsion and Performance Department

DERA DRIC

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

Report documentation page

| | | | |
|---|------------------|---|------------------------------|
| 1. Originator's report number: | | DERA/AS/PTD/CR000103 | |
| 2. Originator's Name and Location: | | David S. Lee DERA Pyestock | |
| 3. Contract number and period covered: | | EPG 1/1/95 | |
| 4. Sponsor's Name and Location: | | DETR, London | |
| 5. Report Classification and Caveats in use: | 6. Date written: | Pagination: | References: |
| UNCLASSIFIED | Jan.–Sept. 2000 | 9 + 69 | 113 |
| 7a. Report Title: | | The effects of aviation contrails on global climate | |
| 7b. Translation / Conference details (if translation give foreign title / if part of conference then give conference particulars): | | | |
| 7c. Title classification: UNCLASSIFIED | | | |
| 8. Authors: | | D. S. Lee, P. E. Clare, J. Haywood, B. Kärcher, R. W. Lunnon, I. Pilling, A. Slingo and J. R. Tilston | |
| 9. Descriptors / Key words: | | Aviation, contrails, global climate | |
| 10a. Abstract. | | | |
| <p>Persistent contrails and aviation-induced cirrus coverage are amongst the effects that aviation has on radiative forcing of climate, as identified by the Intergovernmental Panel on Climate Change's 1999 report '<i>Aviation and the Global Atmosphere</i>'. Although these effects are potentially the largest, they have the most uncertainty associated with them.</p> <p>This report summarises state of knowledge on the effect of persistent contrails and aviation-induced cirrus on radiative forcing of climate in relation to current uncertainties. These uncertainties are discussed and the requirements of reducing these uncertainties identified. Research recommendations to reduce these uncertainties are made.</p> | | | |
| 10b. Abstract classification: | | UNCLASSIFIED | FORM MEETS DRIC 1000 ISSUE 5 |

UNCLASSIFIED

DERA/AS/PTD/CR000103

UNCLASSIFIED