Systematic review of the impact of emissions from aviation on current and future climate

A technical report by the University of Southampton


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Greener by DESIGN

Systematic review of the impact of emissions from aviation on current and future climate

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None declared.

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EXECUTIVE SUMMARY

Aviation emissions have an impact on the global climate, and this is consequently an active area of research worldwide. By adapting replicable and transparent systematic review methods from the field of evidence-based medicine, we aim to synthesise available data on the effects of aviation emissions on climate. From these data, we aim to calculate lower and upper bounds for estimates of the effect of aviation on climate in an objective manner.

For the systematic review an appropriate protocol was developed and applied by two independent reviewers, to identify research that met the inclusion criteria. These included all aviation types, original research studies, climate models with aviation as a specific component, with outcomes for emissions, radiative forcing, global warming potential and/or surface temperature changes. These studies were prioritised and data extracted using a standard process. The 35 studies reviewed here reported radiative forcing, global warming potential and/or temperature changes as outcomes, allowing direct comparisons to be made.

Tabulated results and a narrative commentary were provided for overall effects on climate, and the individual effects of carbon dioxide, water, contrails, cirrus clouds, ozone, nitrogen oxides, methane, soot and sulphur oxides. Lower and upper bounds for these effects, and their relative contributions compared to overall radiative forcing and surface temperature changes, have been described.

This review shows that the most recent estimates for the contribution of aviation to global climate are highly dependent on the level of scientific understanding and modelling, and predicted scenarios for social and economic growth. Estimates for the future contribution of aviation to global radiative forcing in 2015 range from 5.31% to 8.04%. For 2050 the estimates have a wider spread, from 2.12% to 17.33%, the latter being for the most extreme technology and growth scenario. These global estimates should be considered within the context of uncertainties in accounting for the direct and indirect effects of different contributions. Variations between lower and upper bounds for estimates of radiative forcing are relatively low for carbon dioxide, around 131%, to 800% for cirrus clouds effects, and 1044% for soot. Advances in climate research, particularly in the area of contrail and cloud effects, has led to some revision of the 1999 IPCC estimates[1], and demonstrates that the research community is actively working to further understand the underlying science.

The approaches assumptions, limitations and future work were discussed in detail. We have demonstrated how the systematic review methodology can be applied to climate science, in a replicable and transparent manner.

Percentage variation of radiative forcing results (high versus low bound)

Effect	**Percentage variation of radiative forcing results (high versus low bound)**			
	1990	**2000**	**2015**	**2050**
CO_2	131%	116%	121%	112%
Water	-	-	375%	420%
Contrails	-	340%	588%	676%
Cirrus	-	-	800%	-
Ozone	-	132%	135%	1071%
NO_x	186%	-	195%	-
Methane	-	173%	133%	1044%
Soot	-	160%	150%	150%
SO_x	-	114%	-	-
Overall	**-**	**149%**	**142%**	**551%**

Aviation's contribution to global emissions

Effect	**Percentage of global radiative forcing**							
	1990		**2000**		**2015**		**2050**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
% global RF, A1F1 [1]	4.66%	-	3.59%	5.34%	5.34%†	7.56%†	2.12%	11.68%
% global RF, B1[1]	4.66%	-	3.59%	5.34%	5.31%†	7.67%†	3.10%	17.09%
% global RF, IS92a [1]	4.66%	-	3.65%	5.42%	5.67%†	8.04%†	3.15%	17.35%

† Based on linearly interpolated value for global radiative forcing between 2010 and 2020 from Penner *et al* (1999)[1]

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NOMENCLATURE

1D, 2D, 3D	One dimensional, two dimensional, three dimensional
A1F1	IPCC scenario
AGWP	Absolute global warming potential
AMIP	Atmospheric model intercomparison project
ARPEGE/Climat	Météo France climate model
B1	IPCC scenario
BC	Black carbon
C	carbon
CAB	Commonwealth Agricultural Bureaux
CCI	Cirrus cloud insertion
CO_2	Carbon dioxide
CTM	Chemical transport model
cryo	cryoplane
cryo1-cryo3	Model scenarios (cryoplanes)
DfT	Department for Transport (UK)
DLR	Deutsche Zentrum für Luft- und Raumfahrt
Dyn.	dynamical
EDF	Environmental defence fund
Edh	IPCC scenario
GCM	General circulation model or global climate model
GCMAM	Global climate middle atmosphere model
GISS	Goddard Institute for Space Studies
GWP	Global warming potential
Eab	IPCC scenario
ECHAM	European Centre Hamburg Model
ECMWF	European Centre for Medium range Weather Forecasting
EU	European Union
Fa1	IPCC scenario
Fa2	IPCC scenario
FA1H	IPCC scenario
FAST	Aviation forecast model
Fc1	IPCC scenario
Fe1	IPCC scenario
FESG	Forecasting and economic support group
g	grams
HadAM3-STOCHEM	Hadley Centre climate model
HCC	High cloud cover
hPa	Hectopascal (1 millibar)
HSCT	High speed civil transport
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRC	Information Resources Centre, University of Southampton, UK

IS92a	IPCC scenario
K	Kelvin
ke	kerosene
Ker	Model scenario (kerosene aircraft)
Kft	1000 feet
Kg	kilogram
km	kilometre
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Dutch Meteorological Institute)
LMDz-INCA	le Modèle de Circulation Générale du LMD chemistry model
MLO	Mixed layer ocean (model)
MOGUNTIA	Model of the Global Universal Tracer transport In the Atmosphere
mg	milligrams
mK	milliKelvin (10^{-3} Kelvin)
N	nitrogen
NA	Not applicable
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
n/s	Not (statistically) significant
ppbv	Parts per billion volume
ppmv	Parts per million volume
R	Model scenario
RCM	Radiative convective model
REPROBUS	le Modèle de Circulation Générale du LMD 3D chemistry transport model
RF	Radiative forcing
RFI	Radiative forcing index
RIVM	National Institute for Public Health and the Environment (Dutch)
RTM	Radiative transfer model
S	Scaling factor
SD	Standard deviation
SO_4	sulphate
SO_x	Sulphur oxides
SRES	IPCC scenario
SUNNYA-CCM3	Global climate model
Tg	Teragram (10^{12}g)
TOMCAT	Chemistry Transport Model
TRADEOFF	EU Fifth Framework project. ”Aircraft emissions: contribution of different climate components to changes in radiative forcing - TRADEOFF to reduce atmospheric impact”
ULAQ	University of L’Aquila chemistry transport model
Yr or y	year
µm	Micrometer ($10^{-6\ m}$)

1 AIM OF THE REVIEW

Aviation emissions have an impact on the global climate, and this is consequently an active area of research worldwide. By adapting replicable and transparent systematic review methods from the field of evidence-based medicine, we aim to synthesise available data on the effects of aviation emissions on climate. From these data, we aim to calculate lower and upper bounds for estimates of the effect of aviation on climate in an objective manner.

2 INTRODUCTION

The global climate is sensitive to greenhouse gases, and indirect effects of other compounds. This is of concern for future evolution of the climate, with global temperature increases being predicted to have a significant effect on the planet. The ecosystem is complex, and both natural and anthropogenic effects can be significant, with coupling of the atmosphere, ocean and landmass behaviour all contributing to the overall climate response. Computer simulation models can be used to investigate future scenarios, and show how different contributions to the overall climate behave. This information is useful to help guide policymakers to make decisions about how best to mitigate climate change.[2] There are, however, different levels of uncertainty regarding the underlying science that must be taken into account in any discussion. It is only by looking at the full range of research that meaningful conclusions can be drawn. The aim of this systematic review is to provide an objective account of the current state-of-the-art research on the effects of aviation on the global environment. It is hoped that this will help to provide a more solid foundation for discussions on this topic.

2.1 Aircraft emissions

Aircraft, like other forms of transport, produce emissions that can have an impact on the global climate. Carbon dioxide (CO_2) and water vapour are the main emissions from aircraft, with nitric oxide, nitrogen dioxide (collectively termed NO_x), sulphur oxides (SO_x) and soot also contributing.[1] Gases and particles from aircraft are emitted directly into the upper troposphere and lower stratosphere. Here, they alter concentrations of carbon dioxide, ozone (O_3) and methane (CH_4). Other climatic effects include the formation of condensation trails (contrails), and possible increases in cirrus cloudiness.[1]

Radiative forcing, measured in Wm^{-2}, is a calculation of impact on the energy balance of the Earth-atmosphere system. A positive value implies a global warming effect, and a negative value indicates cooling.[1] CO_2 remains in the atmosphere for around 100 years, and so CO_2 from aircraft emissions becomes mixed with CO_2 from other sources, having a global warming effect. However, water vapour, NO_X and other emissions have shorter residence times, and they remain concentrated around flight routes. This leads to more localized increases in radiative forcing.[1]

NO_x has an effect at cruising altitudes, typically in the upper troposphere and lower stratosphere, which enhances ozone production and reduces methane concentrations.

Residence times of ozone are a few months. The effect of ozone in this region of the atmosphere is to enhance the radiative forcing. The effect of reducing methane levels has a negative radiative forcing effect, although the residence time of methane is of the order of a decade.

Evaluation of the effects of aviation emissions on climate provides a range of uncertainties, based on current climate research. This ranges from relatively confident assessments of CO_2 effects, to poor confidence in the effect of contrails and cirrus clouds. The relative importance of different contributors means that overall levels of uncertainty on the combined effect on climate are substantial, and a major focus of current efforts is to improve fundamental understanding of atmospheric processes, to help reduce these uncertainties.

Climate models provide a way of predicting future climate behaviour, and allow different scenarios to be investigated. Such simulations rely on representative input data and accurate mathematical modelling of physical processes. Both of these factors are sources of uncertainty that cannot be eliminated.

2.2 Current situation

The Intergovernmental Panel on Climate Change (IPCC) produced a report on aviation and the global atmosphere in 1999.[1] Since then, numerous reports, review articles and newspaper columns have debated the link between aviation and global warming. There is often a lack of clarity surrounding the underlying data used in reviews, particularly with regard to the large error margins and variety of scenarios which are often assumed with climate models. High quality scientific research in the area of aviation and the environment is being carried out worldwide, and it is apparent that the level of scientific understanding on this subject is variable. The prediction of future scenarios as the basis for policymaking is an area in which levels of uncertainty should be well defined and understood. This is particularly true where changes in aircraft operational and design goals are put forward based on the climate science. Continuous progress through research programmes, particularly in Europe and the USA, means that the science is improving.

2.3 Systematic review – a novel approach in this field

The aim of this study is to provide an objective, quantitative survey of recent research into the effects of aviation on climate. Formal systematic review methodology is well established in the field of evidence-based medicine,[3;4] but has not yet been widely adopted in engineering and climate sciences. Systematic reviews aim to minimise bias by using well-documented, reproducible methodology to synthesise available data on a particular research question. There are four key stages to a review (development of a protocol, identification of studies, quality assessment, data extraction and synthesis of data), as shown in Figure 1.

This study applies the systematic review methodology to the subject of aviation's effect on the global environment. The development of the full methodology for this review is discussed in more detail in Section 3. The results from the data extraction stage are described in Section 3. A general discussion of the methodology, results and suggestions for future work are given in Section 4, followed by conclusions in Section 5.

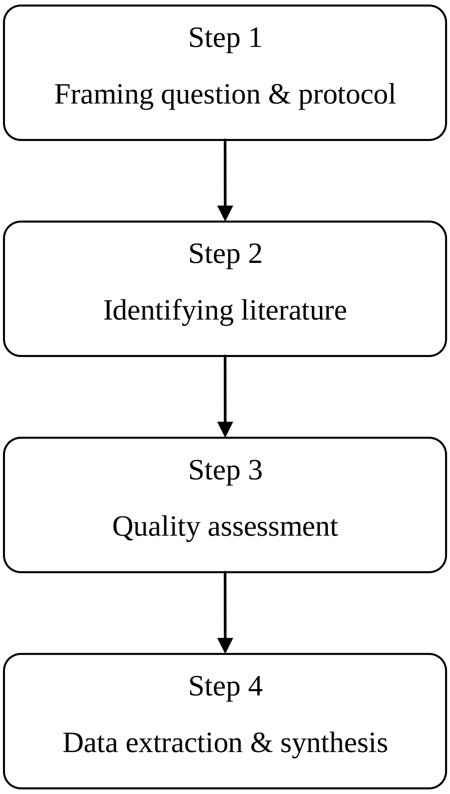

Figure 1. Systematic review methodology

3 METHODOLOGY

The study aims to perform a systematic review of the effects of aviation emissions on the global environment for current and future scenarios. The first stage of the systematic review process was to develop a research protocol, outlining the review's proposed search strategy and methodology. The protocol was circulated to experts in the field, and amended in light of their comments. A key part of the protocol was the development of criteria for deciding which studies to include in the review.

3.1 Search strategy

An experienced information officer developed and tested a search strategy, designed to identify studies reporting aviation emissions and their effect on climate and climate models. This was then applied to key databases and sources of information to retrieve a list of titles and abstracts of relevance to the systematic review. The search strategy for Web of Science is included in Appendix 1. A number of electronic databases were searched, including: Web of Science; Engineering Village; Scopus; CAB Abstracts; DfT Research Database. Other web-based resources included the Tyndall Centre; the Environmental Change Institute and the United Nations Framework Convention on Climate Change.

3.2 Inclusion and exclusion criteria

References retrieved during the searches were stored in a database using the Reference Manager software package. Two reviewers independently scanned through the titles and abstracts to discard any articles which clearly did not meet the inclusion criteria pre-defined in the protocol, and outlined in Sections 3.2.1-3.2.3. References which were likely to be suitable for the review were retrieved as full papers for closer inspection. The retrieved full papers were then screened by two independent reviewers checking against the inclusion criteria. By scanning the database independently, the risk of selection bias in study selection was minimised. In cases where reviewers disagreed on whether to include/exclude on the basis of the abstract, the issue was resolved through discussion.

3.2.1 Aviation type

- Commercial passenger aircraft
- Freight
- General, unspecified aviation
- Military aviation, where data are available

All types of aviation were included, although not all papers necessarily refer to all types of aviation.

3.2.2 Outcomes

Studies reporting one or more of the following outcomes were initially included in the systematic review:

- Carbon dioxide (CO_2)
- nitric oxide (NO) and nitrogen dioxide (NO_2), collectively known as nitrogen oxides (NO_X)
- Water vapour, including clouds and contrails
- Particulates, including sulphur oxides (SO_X) and soot
- Radiative forcing (RF)
- Global warming potential (GWP)
- Effect of emissions on global climate models

However, as will be discussed in Section 4.1, it became necessary to amend the protocol and prioritise the retrieved studies so that only those reporting radiative forcing, global warming potential or temperature effects were included in this stage of the review. This prioritisation was done after the screening stage, and hence did not influence study identification. This is discussed further in Section 4.

3.2.3 Types of studies

The following types of study were included:

- Climate models with aviation as a specific component
- Only original research articles were included, whether these presented original data or were review papers presenting an interpretation of existing model data. Editorials and newspaper articles reporting the results of other reviews were not included.
- Conference abstracts from the last two years were screened, and were considered for inclusion where sufficient data were presented.

It was initially intended to include studies reporting emissions from aircraft, but the sheer volume of references made this impractical for the present study. The protocol's inclusion criteria were therefore amended to exclude studies which reported emissions estimates but did not include a climate model. Although these studies were excluded from the present review, they were marked in the database for any future work in this area.

It was not possible to include non-English language studies in the present review, due to the extra resources that would be required for translation. The potential for publication bias is discussed in Section 5.

3.2.4 Data extraction strategy

A standard data extraction template was used to standardise the information taken from the papers included in this study. This required reviewers to record details of the studies' methodology, key results and quality. Studies were data extracted by one reviewer, and checked by a second reviewer to minimise the risk of errors in reporting results. The data extraction form was developed at the protocol stage of the review. A typical form is shown in Appendix 2.

3.3 Quality assessment strategy

Quality assessment is an important part of the systematic review methodology. By assessing the studies' quality against standard criteria, the results of the studies contributing to the review can be assessed in the context of any limitations of the underlying model structure. Unlike systematic reviews in medicine, no standard quality assessment criteria exist for this area. Review-specific criteria were therefore developed for this review, using an adaptation of the Drummond Checklist[5] for evaluating models of cost-effectiveness in the field of healthcare. The original checklist developed for this review was circulated to experts for comment and revision before being used in the review. Quality assessment criteria were applied by one reviewer and checked by a second, with any differences of opinion being resolved through discussion. The criteria developed for this review are shown below:

- Did the study use a validated climate model?
- Was the study reporting an original model/ novel analysis?
- Did the study involve a comparison of alternatives?
- Was the potential bias of input data established?
- Did the study investigate/ report variability around emissions?
- Did the study report variability around the climate model's physical inputs and assumptions?
- Were all the important and relevant parameters for each alternative scenario identified?
- Were the results compared with those of others who have investigated the same question?

3.4 Methods of analysis/synthesis

Evidence from the systematic review was synthesised through tabulation of results and a narrative review. Standard methodology and software[a] exist for performing meta-analysis of clinical trials of pharmaceutical drugs.[3;6] However, heterogeneity in study design, model type, parameters and time horizons meant that meta-analysis of key outcomes would have been inappropriate here. Section 3 contains the narrative review and tabulated results, with a general discussion of the results, limitations and assumptions given in Section 4.

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[a] Review Manager software, available via the Cochrane Library

4 RESULTS

4.1 Quantity and quality of literature

Scoping searches for this project identified over 2000 references. Inclusion criteria were therefore made more restrictive to include a requirement that the study mentioned results of models/simulations (see search strategy for Web of Science, Appendix 1). Searches of the scientific literature and of relevant government reports/websites identified 579 such references. The number of references identified at each stage of the review is shown in Figure 2. References which were retrieved as full papers for further inspection but which did not meet the inclusion criteria are listed in Appendix 3, with reasons for exclusion.

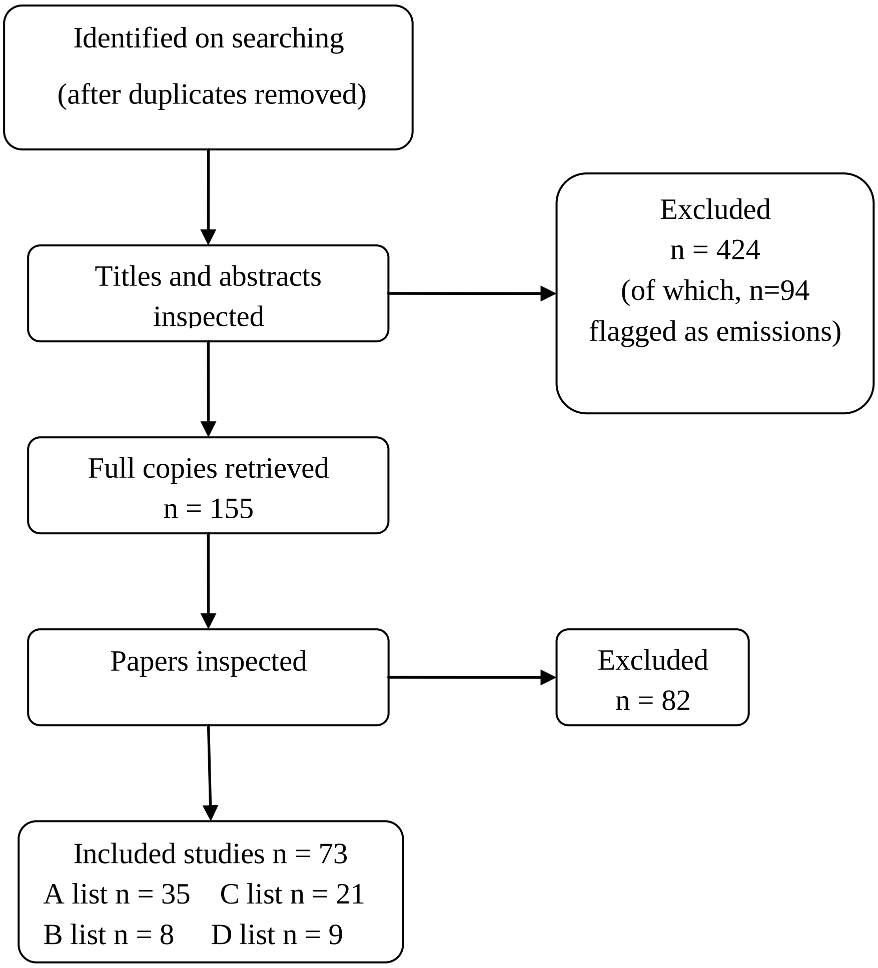

Figure 2. Number of studies identified at each stage of the review

After screening, papers were prioritised into categories shown in Table 1, due to the large number of references and limited resources available to the project. Due to these constraints, only results for the priority A papers are included in this study. This included papers that specifically reported temperature, radiative forcing and/or global warming potential as outcomes.

Table 1. Priorities for data extraction

Priority	Description
A	Climate model with RF/GWP/temperature as outcome
B	Modelled CO_2, black carbon, sulphur, contrails etc. but no specific RF/GWP/temperature output
C	Modelled NO_x or ozone but no RF/temperature output (e.g. chemistry transport models)
D	HSCT/cryoplanes with no current technology scenarios

Systematic reviews of clinical trials are more straight forward, as trial design and reporting of outcomes is usually more standardised. In the case of aviation and climate research, researchers present different metrics for their research output, making it difficult, if not impossible, to make direct comparisons. The priority A papers do, at least, provide common outcome metrics, even though the input data and model design may differ. Section 3.2 attempts to group the results so that direct comparisons can be made, where possible. It is hoped that this shows that the systematic review concept is valid in this domain, even if the review methodology is less straightforward to implement than in more established fields in which this approach is used. Data extraction, analysis and commentary for the priority B-D papers are areas for future investigation, although the more disparate nature of the research outcomes will make this a challenging task.

Given the high number of studies meeting the inclusion criteria, we prioritised them using the criteria in Table 1. The present review covers priority A papers, with papers classified as priorities B, C and D listed in Appendix 4.

The present review covers priority A papers, with papers classified as priorities B, C and D listed in Appendix 4. The characteristics of the 35 priority ‘A’ studies which met the inclusion criteria are shown in Table 2. The quality assessment results for the priority A papers are shown in Table 3, with papers ranked by how many quality criteria were met. The data is summarised in Figure 3.

The quality of input data, methodology and reporting was generally of a high standard when compared against the assessment criteria developed for this study’s protocol, with over 28% meeting all quality criteria, and 40% of the papers meeting three-quarters of the quality criteria. All of the papers included original models or novel data analysis, which was part of the inclusion criteria. 74% reported some comparison of alternative modes or scenarios. These studies were sensitive to the input data, and the assumed future growth scenarios. In 74% of the papers any potential bias of the input results was established, with 46% reporting the variability around emissions. 63% of the papers reported relevant parameters that were used for any alternative scenarios that were investigated. 89% included some comparison with other studies looking at the same research question.

The priority A studies identified during the systematic review reported the results of a variety of models. The majority of the studies included in this systematic review were from peer-reviewed journals. A number of them were concerned with modelling the effect of current and future aircraft emissions on the global climate, reporting RF, GWP or temperature changes.

These typically made use of global climate models, and aimed to include the major atmospheric chemistry. Of the 35 included studies, 28 used a validated climate model (80%). Papers which did not use a validated climate model tended to be reports of 1D or 2D numerical parameterisation studies, often with a focus on chemistry tracing. A number of offline chemistry transport and radiative transfer models were used to investigate the particular effect of certain emissions. Parametric studies, sometimes using unrealistically high input values, were included that illustrate particular climate response. Section 4.2 discusses the results presented in the included studies.

Table 2 Characteristics of included studies

First author and date	**Model used**	**Description of study**	**Key climate output(s)**
Bernsten *et al*. 2000[7]	OsloCTM-1 (Oslo university CTM)	Model of radiative forcing associated with tropospheric ozone	RF
Danilin *et al*., 1998 [8]	Eleven 2D and 3D models	Aviation fuel tracer simulations to calculate an upper limit for aircraft-produced effects, and uncertainty ranges	paper focussed on fuel tracer results (not data extracted) but RF also mentioned.
Dessens *et al*. 2002 [9]	REPROBUS 3D CTM, with ARPEGE/climat GCM	The effects of NOx from future subsonic and supersonic planes on atmospheric ozone, and the related change in mean annual zonal temperatures	Mean annual zonal temperatures
Fichter *et al*. 2005[10]	ECHAM GCM	Impact of cruise altitude on contrails, and related radiative forcing	Contrail coverage; RF
Forster *et al*., 2006 [11]	Numerical model and carbon cycle model (no details given)	An investigation into the appropriateness of emission trading schemes, and in particular the inappropriate use of the radiative forcing index (RFI)	Absolute GWP; emissions weighting factor
Fortuin *et al*., 1995 [12]	Radiative transfer model based on ECMWF	Model of greenhouse effect of aircraft emissions	fixed temperature forcing; fixed dynamical heating forcing
Fuglesvedt 1996 [13]	2D photochemistry transport model	Model of the effects of changed emissions on the levels of ozone, hydroxyl radicals and methane.	sustained GWP
Gauss *et al*. 2003 [14]	OSLO CTM-2; SUNNYA-CCM3 GCM	Perturbations in H_2O caused by aircraft in the year 2015 are calculated with a CTM and used as input for radiative forcing calculation in a GCM. Main focus is on cryoplanes, but kerosene scenarios also included.	H_2O from CTM; RF from GCM

First author and date	Model used	Description of study	Key climate output(s)
Isaksen *et al*., 2001 [15]	OSLO CTM	Model of the impact of aircraft emissions on atmospheric ozone and methane lifetime. Calculated changes in the global distribution of ozone and methane then used to calculate RF of current and future (2015 and 2050) fleets of subsonic aircraft.	RF
Johnson *et al*., 1996 [16]	2D CTM	Model of transport of trace gases and calculation of their radiative impact/global warming potential.	GWP; RF
Marquart *et al*., 2001 [17]	Calculations of RF, methods vary depending on emission type. Some based on ECHAM climate model.	Model of kerosene vs. hydrogen planes, future scenarios	RF, overall and due to: CO_2, O_3, CH_4, H_2O, contrails, sulphates, soot
Marquart *et al*., 2003 [18]	Calculations added to ECHAM GCM	Development of a contrail parameterization for the ECHAM GCM	contrail cover; RF
Marquart *et al*., 2005 [19]	GCM with contrail parameterisation [ECHAM4.L39 (DLR)]	An updated estimate of the radiative forcing of a hypothetical fleet of cryoplanes compared with a conventional aircraft fleet (update of Marquart *et al* 2001).	RF
Meerkötter *et al*. 1999 [20]	Radiative transfer model	Parametric study of the instantaneous radiative impact of contrails	RF
Minnis *et al*., 1999 [21]	Radiative transfer model	Model of radiative forcing by persistent linear contrails	RF
Morris *et al*., 2003 [22]	Trajectory model	Model of the effect of aircraft exhaust on water vapour in the lower stratosphere, and calculations of radiative forcing.	water vapour; RF
Myhre *et al*., 2001 [23]	Multistream model	Global calculations of radiative forcing due to contrails from aircraft. Contrail distribution was computed based on aviation fuel consumption and radiative transfer models for solar and thermal infrared radiation.	RF
Penner *et al*. 1999 [1]	3D chemical transport models (online & offline)	IPCC intercomparison of models	RF, greenhouse gas emissions and

First author and date	**Model used**	**Description of study**	**Key climate output(s)**
			concentrations
Pitari *et al* 2002 [24]	3D CTM (ULAQ model)	Modelling the effect of sulphate particles on RF	RF
Ponater *et al*., 1996 [25]	ECHAM 3D GCM	Model of the global atmospheric response to aircraft water vapour emissions and contrails	solar radiation; thermal radiation; net radiation
Ponater *et al*., 1999 [26]	Atmospheric GCM (ECHAM4) coupled to a mixed layer ocean model (MLO) CTMs used for ozone data - MOGUNTIA used as basis for some of the scenarios	Modelled effect on the climate of ozone changes caused by present and future air traffic.	climate response; surface air temperature; RF
Ponater *et al*., 2002 [27]	Novel parameterization of contrails added to ECHAM4	Parameterization of contrails for use in global climate models, and resulting modelled radiative forcing of contrails.	RF
Ponater *et al*., 2005 [28]	ECHAM4 GCM with amendments for contrails and with a mixed layer ocean model	Model of climate sensitivity parameter to contrail cirrus	climate sensitivity parameter; mean surface temperature
Ponater *et al*., 2006 [29]	ECHAM4 GCM	Model of the potential reduction in climate impact by switching from kerosene to liquid hydrogen fuelled planes	RF; surface temperature
Rind *et al*., 1995 [30]	Goddard Institute for Space Studies climate/middle atmosphere model (GISS/GCMAM).	Modelled experiments of ozone and water vapour perturbations. One scenario includes an aircraft component.	sea surface temperature, air temperature
Rind *et al*., 1996 [31]	Goddard Institute for Space Studies (GISS) global climate middle atmosphere model	Model of the climatic effect of water vapour release	surface air temperature
Rind *et al*., 2000 [32]	Goddard Institute for Space Studies (GISS) global climate middle-atmosphere model (GCMAM).	Model of the climatic impact of cirrus cloud increases along aircraft flight paths	surface air temperature; RF
Sausen *et al*., 1997	ECHAM4 GCM	Modelling the effect of aircraft induced ozone changes on the global	mean temperatures

First author and date	Model used	Description of study	Key climate output(s)
[33]		climate	
Sausen *et al*., 2000 [34]	Combination of linear response models	Model of climate response to emissions scenarios	CO_2 concentration, global mean sea surface temperatures, sea level changes
Sausen *et al*., 2005 [35]	Five CTMs and Climate Chemistry Models: TOMCAT, CTM-2, ECHAM4.L39, LMDz-INCA, ULAQ	New estimates of RF from number of climate models, to update IPCC (1999) estimates for 2000.	RF, with and without cirrus cloud forcing
Stevenson *et al*., 2004 [36]	HadAM3-STOCHEM climate-chemistry model.	Model of radiative forcings generated by aircraft NOx emissions through changes in ozone and methane.	RF
Stordal *et al*., 2005 [37]	Regression analysis between trends in cirrus cloud and aircraft traffic density; cirrus cloud cover then multiplied by RF of cirrus to get overall RF from aviation. Based on FAST	An investigation of trends in cirrus cloud cover due to aircraft traffic, and calculations of RF from this.	RF
Strauss *et al*., 1997 [38]	1D radiative convective model (RCM)	Model investigating the impact of contrail-induced cirrus clouds on regional climate (southern Germany).	solar and ice cloud radiative properties
Valks *et al*., 1999 [39]	CTM – RIVM version of MOGUNTIA	Model of the effect of present and future NOx emissions from aircraft on the atmosphere, and the corresponding RF	RF
Williams *et al*., 2002 [40]	Numerical model (no further details)	Model of the effect of cruising altitude on the climate change impacts of aviation. The rationale for restricting cruising altitude is to reduce contrail formation.	% change in fuel burn; altered flight times; RF estimated, but not really an output of model calculations.

RF = radiative forcing; GWP=global warming potential; GCM=global climate model; CTM=chemistry transport model

Table 3 Quality assessment of included studies ranked by quality assessment score

	Did the study use a validated climate model?	**Was the study reporting an original model/ novel analysis?**	**Did the study involve a comparison of alternatives ?**	**Was the potential bias of input data established ?**	**Did the study investigate/ report variability around emissions?**	**Did the study report variability around the climate model's physical inputs and assumptions?**	**Were all the important and relevant parameters for each alternative scenario identified?**	**Were the results compared with those of others who have investigated the same question?**	**Overall assessment score (total no. of 'Y' scores)**
Fichter *et al*. 2005[10]	Y	Y	Y	Y	Y	Y	Y	Y	8
Gauss *et al*. 2003 [14]	Y	Y	Y	Y	Y	Y	Y	Y	8
Marquart *et al*., 2003 [18]	Y	Y	Y	Y	Y	Y	Y	Y	8
Minnis *et al*., 1999 [21]	Y	Y	Y	Y	Y	Y	Y	Y	8
Penner *et al*. 1999 [1]	Y	Y	Y	Y	Y	Y	Y	Y	8
Ponater *et al*., 1996 [25]	Y	Y	Y	Y	Y	Y	Y	Y	8
Ponater *et al*., 2002 [27]	Y	Y	Y	Y	Y	Y	Y	Y	8
Ponater *et al*., 2006 [29]	Y	Y	Y	Y	Y	Y	Y	Y	8
Sausen *et al*., 2000 [34]	Y	Y	Y	Y	Y	Y	Y	Y	8
Strauss *et al*., 1997 [38]	Y	Y	Y	Y	Y	Y	Y	Y	8
Bernsten *et al*. 2000 [7]	Y	Y	N	Y	Y	Y	Y	Y	7
Pitari *et al* 2002 [24]	Y	Y	Y	N	Y	Y	Y	Y	7
Rind *et al*., 1996 [31]	Y	Y	Y	Y	NA	Y	Y	Y	7
Sausen *et al*., 2005 [35]	Y	Y	N	Y	Y	Y	Y	Y	7

	Did the study use a validated climate model?	**Was the study reporting an original model/ novel analysis?**	**Did the study involve a comparison of alternatives ?**	**Was the potential bias of input data established ?**	**Did the study investigate/ report variability around emissions?**	**Did the study report variability around the climate model's physical inputs and assumptions?**	**Were all the important and relevant parameters for each alternative scenario identified?**	**Were the results compared with those of others who have investigated the same question?**	**Overall assessment score (total no. of 'Y' scores)**
Dessens *et al*. 2002 [9]	Y	Y	Y	?	?	Y	Y	Y	6
Marquart *et al*., 2005 [19]	Y	Y	Y	Y	?	?	Y	Y	6
Ponater *et al*., 1999 [26]	Y	Y	Y	Y	?	?	Y	Y	6
Ponater *et al*., 2005 [28]	Y	Y	N	Y	Y	Y	?	Y	6
Rind *et al*., 2000 [32]	Y	Y	Y	Y	NA	Y	?	Y	6
Valks *et al*., 1999 [39]	Y	Y	Y	?	N	Y	Y	Y	6
Fuglesvedt 1996 [13]	Y	Y	N	?	Y	Y	N	Y	5
Morris *et al*., 2003 [22]	N	Y	Y	?	N	Y	Y	Y	5
Myhre *et al*., 2001 [23]	N	Y	Y	?	N	Y	Y	Y	5
Rind *et al*., 1995 [30]	Y	Y	Y	Y	N	Y	?	?	5
Stevenson *et al*., 2004 [36]	Y	Y	Y	Y	N	?	?	Y	5
Stordal *et al*., 2005 [37]	N	Y	N	Y	Y	?	Y	Y	5
Isaksen *et al*., 2001 [15]	Y	Y	Y	N	N	N	N	Y	4
Marquart *et al*., 2001 [17]	Y	Y	Y	N	?	?	Y	N	4
Sausen *et al*., 1997 [33]	Y	Y	Y	N	?	?	?	Y	4

	Did the study use a validated climate model?	**Was the study reporting an original model/ novel analysis?**	**Did the study involve a comparison of alternatives ?**	**Was the potential bias of input data established ?**	**Did the study investigate/ report variability around emissions?**	**Did the study report variability around the climate model's physical inputs and assumptions?**	**Were all the important and relevant parameters for each alternative scenario identified?**	**Were the results compared with those of others who have investigated the same question?**	**Overall assessment score (total no. of 'Y' scores)**
Danilin *et al*., 1998 [8]	Y	Y	N	N	N	N	N	Y	3
Forster *et al*., 2006 [11]	N	Y	Y	N	N	N	?	Y	3
Fortuin *et al*., 1995 [12]	N	Y	N	N	N	N	?	Y	2
Johnson *et al*., 1996 [16]	Y	Y	N	?	N	N	N	N	2
Meerkötter *et al*. 1999 [20]	N	Y	N	?	N	N	?	Y	2
Williams *et al*., 2002 [40]	N	Y	Y	N	N	N	N	N	2

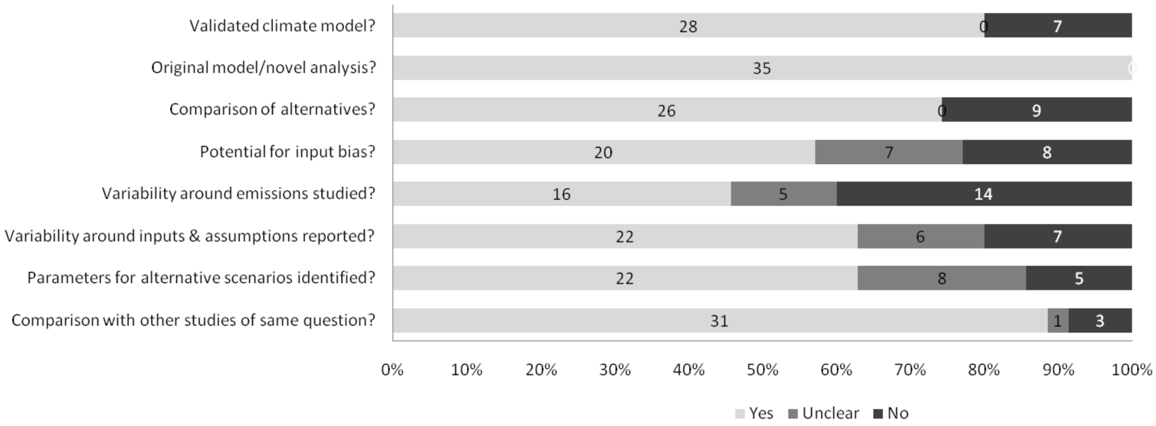

Figure 3. Quality assessment summary

4.2 Assessment of effects of aviation emissions

Results of the included studies are presented in this section. These 35 papers covered a range of original research studies that modelled the effect of aviation on the atmosphere, with outcomes measured in terms of RF, GWP or temperature changes. A range of scenarios was used, in terms of aircraft traffic, model types and parameters. The inputs and major outcomes are summarised in Table 4 - Table 9. The review aims to synthesise the results of these studies in a coherent manner, so that the reader is able to gain an understanding of the current state of the science. This section is sub-divided to separately describe papers presenting results of aviation's overall effect on RF, GWP and temperature, and that due to carbon dioxide; water, contrails and cirrus clouds; and ozone and aerosols. Where papers are relevant to more than one sub-section they are discussed in turn. While the issue of hydrogen fuelled cryoplanes was not the focus of this review, results from studies which presented data for both cryoplanes and kerosene-fuelled fleets are included, and discussed as a matter of interest for the reader. An overall summary of the results is given in section 3.2.5.

4.2.1 Overall effect of aviation on RF, GWP and temperature

The overall effect of aircraft emissions on the atmosphere, in terms of RF, GWP or temperature variations, is modelled in the five papers reviewed here. The key inputs and outcomes are presented in Table 4.

The IPCC report of Penner *et al*[1] is a detailed cross-comparison of several climate models, and is the most comprehensive study of different aviation scenarios to date. Overall radiative forcing was modelled from 1990 to 2050, with a breakdown of individual effects also described; these are discussed separately in the following sections. The IPCC predictions for 2000 were updated by Sausen *et al*[35] using five different CTM and climate chemistry models, as part of the EU TRADEOFF project, from 0.0713 to 0.0478 Wm^{-2} (excluding cirrus cloud effects). The reduction in RF for 2000 was due to the strongly reduced effect from linear contrails, reflecting progress in the underlying scientific understanding of this area since

Penner *et al*[1]. This is discussed in more detail, and the context of other similar research, in section 3.2.2. The IPCC *Fa1* reference scenario developed by the ICAO Forecasting and Economic Support Group (FESG) using a mid-range growth forecast (3.1% per year) and assuming technology for improved fuel efficiency and NO_x reduction, resulted in RF of 0.114 Wm^{-2} for 2015, and 0.193 Wm^{-2} for 2050.

In addition to the baseline case, a number of other scenarios were presented by Penner *et al*[1]. These included the effect of different air traffic growth rates, introduction of a supersonic fleet of airliners (scenario *Fa1H*), and focussing on certain emission reduction technologies above others. The lower bound was for scenario *Fc1*, representing a low-growth rate of 2.2% per year with a subsonic-only airliner fleet, resulting in an RF of 0.129 Wm^{-2} for 2050. The upper bound was for scenario *Edh*, representing a high growth rate (4.7% per year) and focussed on low NO_x technology, giving an RF of 0.564 Wm^{-2} in 2050.

Marquart *et al*[17] focussed on assessing the impact of the introduction of a fleet of hydrogen-powered cryoplanes in 2015, but also reported kerosene fuelled aircraft as a baseline: 0.111 Wm^{-2} for 2015; 0.132 Wm^{-2} for 2050; and 0.137 Wm^{-2} for 2100. In this study, aviation growth was assumed to stop in 2015, accounting for the difference in RF figures for 2050 and 2100 between this study and that by Penner *et al*[1]. In a similar study, Ponater *et al*[29] also investigated cryoplanes, and produced a baseline RF prediction for a pure kerosene fleet of 0.128 Wm^{-2}. The predictions for the introduction of cryoplanes in 2015 reduced the RF in 2050 to 0.109-0.115 Wm^{-2} from Marquart *et al*[17], or 0.0904 to 0.1074 Wm^{-2} from Ponater *et al*[29].

A surface temperature increase of 0.052K was predicted for 2050 by the IPCC *Fa1* reference scenario. Sausen *et al*[34] used a combination of linear response models to assess temperature changes since 1950, predicting an increase of 0.025K in 2050, leading to 0.047K in 2100. Ponater *et al*[29] estimated temperature increase of 0.041K in 2050 for a kerosene aircraft scenario.

The papers reviewed here represent the key studies for global effects of major aviation emissions on the environment using a range of different growth and technology scenarios. The effects of component emissions and their chemistry on the environment are discussed in more detail in sections 3.2.2 to 3.2.4.

4.2.2 Effects of carbon dioxide on RF, GWP and temperature

Papers specifically investigating the effect of carbon dioxide on RF, GWP and temperature are discussed in this section. The key inputs and outcomes are shown in Table 5.

The IPCC paper of Penner *et al*[1] provided a breakdown of the component contributions to its global predictions. Results for 1992 indicated RF of 0.018 Wm^{-2} due to CO_2. Sausen *et al*[35] scaled the IPCC results to 2000 (0.025 Wm^{-2}) to compare them with their own updated results from the TRADEOFF project of 0.0253 Wm^{-2}. An RF due to CO_2 of 0.074 Wm^{-2} in 2050 was predicted by Penner *et al*[1] for the mid-range *Fa1* scenario. This compares well with the results of Ponater *et al*[29], which predicted 0.0729 Wm^{-2} in 2050. Marquart *et al*[17] predicted a lower RF of 0.061 Wm^{-2} for 2050 and 0.066 Wm^{-2} in 2100 for a kerosene fleet. These last two studies also computed the RF with introduction of a cryoplane fleet in 2015, showing an RF in 2050 due to CO_2 of 0.025 Wm^{-2} (Marquart et el[17]) and between 0.0196 and 0.020 Wm^{-2} (Ponater *et al*[29]).

Fortuin *et al*[12] investigated the effect of RF due to CO_2 from 1943 to 1990, using fixed temperature and fixed dynamical heating assumptions, and reported results for mid-latitude summer and winter. The RF was 0.023 to 0.029 Wm^{-2} for the mid-latitude summer case and 0.018 to 0.023 Wm^{-2} for mid-latitude winter. The study also investigated contributions from water vapour, contrails and aerosols, which are discussed in sections 3.2.3 and 3.2.4.

Forster *et al*[11] discussed the use of a radiative forcing index (RFI) as a metric for assessing the impact of non-CO_2 emissions on the environment. Emissions from 1950 to 2000 were modelled using an exponential growth model, and emissions were then held constant over a 500 year timescale. The Absolute Global Warming Potential (AGWP) was then calculated for 1, 20, 100 and 500 years, and the effect of CO_2 and non-CO_2 effects on the AGWP highlighted. From this the RFI was shown to change significantly with time, highlighting the danger in using RFI to account for non-CO_2 effects in any assessment of aviation emissions.

The results of Sausen *et al*[34] used the IPCC *Fa1* scenario and predicted a temperature increase due to CO_2 of 0.024K by 2050, and 0.047K by 2100. This compares well to an increase of 0.026K by 2050 predicted by Ponater *et al*[29].

4.2.3 Effects of water, contrails and cirrus clouds on RF, GWP and temperature

A significant amount of recent research has focussed on the science of water, contrails and cirrus cloud formation from aircraft at altitude. This is a major source of uncertainty in assessing the impact of aircraft emissions on the global environment, as highlighted by Penner *et al*[1]. In this section 20 papers are reviewed that present original research, with the key inputs and outcomes of each shown in Table 6 - Table 8.

The effect of water vapour on RF in 2000 was studied by Sausen *et al*[35], and was calculated to be 0.002 Wm^{-2}, which is the same as that reported in the IPCC report by Penner *et al*[1]. The radiative transfer model (RTM) study by Fortuin *et al*[12] used simulations up to 1990 and reported RF for mid-latitude regions of between 0.006 and 0.023 Wm^{-2} in summer, and 0.028 and 0.131Wm^{-2} in mid winter using a fixed dynamical heating assumption. Ponater *et al*[25] performed a detailed study of the effect of water vapour, using factors of 10, 100, 1000 and 10000, along with sensitivity studies of cloud cover increase by 0.10, 0.05 and 0.02. The study noted that the effect of clouds was much more than that of the water vapour itself, which produced no detectable large-scale climate signal. It was noted that the experiment used was highly artificial and a much stronger enhancement than would ever occur in reality. Rind *et al*[31] performed a parametric study of water vapour effects on RF using a global climate middle atmosphere model. Experiments using water vapour 0.35, 1.5, 35 and 700 times the 1990 aircraft release values showed a measurable effect in the latter two cases only. The cases of 0.35 and 1.5 times 1990 release amounts showed no consistent trend, and the paper therefore concluded that the effect of water vapour does not have a global impact.

Marquart *et al*[17] calculated the RF effect for kerosene and hydrogen fuelled aircraft. The RF induced by water vapour in 2015 was predicted to be 0.0008Wm^{-2} for kerosene and 0.0019Wm^{-2} for hydrogen fuelled aircraft respectively, with near identical results for 2050 and 2100. Ponater *et al*[29] reported RF of 0.0019Wm^{-2} for kerosene fuelled aircraft in 2050, compared with between 0.0018 and 0.0107Wm^{-2} for three cryoplane scenarios. Gauss *et al*[14] investigated water vapour effects of cryoplanes for 2015 using a variety of scenarios. Their baseline study for kerosene aircraft resulted in an RF of 0.0026Wm^{-2}, compared with a baseline cryoplane case of 0.0065 Wm^{-2} and a worst case RF of 0.0625Wm^{-2} when cryoplane cruising altitude was increased by 3km. The major source of uncertainty was the estimated tropospheric lifetime of aircraft emitted water. The CTM model used here was found to be very sensitive to variations of this parameter. This study only considered water vapour, and not contrail effects.

The overall IPCC assessment of Penner *et al*[1] calculated the RF due to contrails to be 0.100 Wm^{-2} in 2050, and RF due to water to be 0.004 Wm^{-2}. The level of uncertainty associated with the effect of cirrus clouds caused it to be excluded from the reported results. Sausen *et al* [35] used a number of climate models in the TRADEOFF project to update the results of Penner *et al*[1] due to contrails, scaled for 2000 (0.039 Wm^{-2}), to 0.010 Wm^{-2}. The effect of cirrus clouds was estimated to be 0.030Wm^{-2}, but with an upper bound of 0.080Wm^{-2}, which was reported in more detail by Stordal *et al*[37]. Rind *et al*[32] investigated increases in cirrus cloud coverage along aircraft flight paths using a global climate model. For increases in high-level cloud cover from 0.5% to 5%, RF changed from 0.00 to 2.4 Wm^{-2}. Ponater *et al*[28] used artificially elevated traffic levels (20 x *Fa1* inventory) to highlight the effect of cirrus clouds; 3.2% contrail coverage produced an RF of 0.29 Wm^{-2}.

Fichter *et al*[10] calculated the mean net RF due to contrails as part of the TRADEOFF project, and the effect of changing cruise altitude on this for 1992 air traffic data. The baseline case showed an RF, corrected for long wave radiation effects, of 0.0029Wm^{-2}. Increasing cruising altitude by 2000 feet increased RF to 0.0031Wm^{-2}. Reducing altitude reduced RF, with a 6000 feet lower cruising altitude resulting in an RF of 0.0016 Wm^{-2}. Fortuin *et al*[12] used a radiative transfer model to investigate a range of emission effects for 1990. They calculated a local RF due to contrails at mid-latitudes of between -0.15 and 0.30 Wm^{-2} in summer, and 0.05 and 0.30 Wm^{-2} in winter.

Future projections of the effect of contrails were included in the cryoplane studies of Marquart *et al*[17] and Ponater *et al*[29]. Marquart *et al*[17] predicted kerosene fuelled aircraft to contribute an RF of 0.052 Wm^{-2} in 2015 and 2050, compared with between 0.0191 and 0.0929 Wm^{-2} in 2050, calculated by Ponater *et al*[29]. These studies highlight the increased effect of contrails due to the introduction of cryoplanes, with Marquart *et al*[17] estimating RF of 0.081Wm^{-2} in 2015 and 2050, compared with between 0.0156 and 0.0783 Wm^{-2} for the three different cryoplane scenarios reported by Ponater *et al*[29].

More recent results from Marquart *et al*[19] investigated the effect of different contrail particle properties. For non-spherical particles, the estimate for RF due to contrails in 2015 by kerosene fuelled aircraft was 0.0098 Wm^{-2}, compared with 0.012 Wm^{-2} for non-spherical, half-size particles, and 0.0127 Wm^{-2} for spherical, half-size particles. The cryoplane RF in 2015 was 0.008 Wm^{-2} for the non-spherical particles, and 0.013 Wm^{-2} for non-spherical, half-sized particles. The effect of ice water content on future contrail effects was studied by Minnis *et al*[21]. They showed how ice water content of between 0.1 and 0.5 causes corresponding RF due to contrails of 0.049 Wm^{-2} and 0.122 Wm^{-2}, respectively. Meerkötter *et al*[20] compared three different radiative transfer models, varying ice water content. They showed that varying the optical depth of the contrails from 0.2 to 0.5 gave an RF of between 0.01 and 0.03 Wm^{-2} for a 0.1% global mean contrail cover case. A key conclusion of the paper was that the uncertainty of the effect of contrail forcing is a factor of five, due to lack of knowledge of contrail cover and optical depth values.

Myhre *et al*[23] investigated the short wave and long wave contributions to contrail RF using an artificially high 1% contrail cover experiment, and a more realistic 0.09% cover scenario. They highlighted that while short wave radiation provided a negative RF, on balance the net RF was positive, resulting in net RF of 0.12 for both the cloudy and clear condition cases with 1% contrail cover. For the realistic cirrus cloud cover case of 0.09%, the effect of including the diurnal cycle was studied. The net RF dropped from 0.011 Wm^{-2} to 0.009 Wm^{-2} when the diurnal cycle was included. Marquart *et al*[18] performed a similar study, showing RF due to contrails rising from 0.0023 Wm^{-2} in 1992 to 0.0148 Wm^{-2} in 2050.

Ponater *et al*[27] developed a parameterised model for including contrails within the ECHAM4 GCM, relating the contrail coverage and optical properties to the state of the atmosphere at any given time. It also allowed feedback of the contrails on the net climate effect. This paper was one of the first attempts to include such a detailed contrail model in a GCM.

As discussed in Section 3.2.2, Forster *et al*[11] investigated the use of RFI as a metric for climate change. They calculated an AGWP due to contrails, showing that it remains constant with time due to their short-lived nature and hence non-cumulative effect.

Rind *et al*[32] investigated increases in cirrus cloud coverage along aircraft flight paths using a global climate model. The global temperature response was shown to be linear for increases in high-level cloud cover from 0.5% to 5%, with global surface temperature changing by between 0.1ºC and 2.2ºC respectively. Ponater *et al*[28] used artificially elevated traffic levels (20 x *Fa1* inventory) and reported that a 3.2% contrail coverage produced a surface temperature increase of 0.082K.

Strauss *et al*[38] developed a 1D radiative convective model and studied the effect of increased cloud cover over Southern Germany, varying the ice particle size from 2µm to 2000µm. A 10% increase in cloud cover was reported to lead to a surface temperature increase of 1.1 to 1.2K in July, and from 0.8 to 0.9K in October. Their model of current contrail cloud cover over Europe, near 0.5%, results in a surface temperature increase of 0.05K.

4.2.4 Effects of ozone, NO_x and aerosols from aviation on RF, GWP and temperature

The direct and indirect effect of aerosols, NO_x and ozone on the atmosphere are studied in the 18 papers included in this section. Nitrogen oxides enhance ozone production and reduce methane concentrations. Soot and sulphur dioxide also affect the climate response, both directly and indirectly. The effect of water vapour is discussed in section 3.2.3. The key input and outcomes are presented in Table 9.

The IPCC report of Penner *et al*[1] provides a breakdown of RF due to ozone, methane, sulphate aerosol and soot aerosol for the period 1990 to 2050. The values for the *Fa1* scenario for ozone and methane for 2015, from NO_x, are 0.040 Wm^{-2} and -0.027 Wm^{-2} respectively. These compare with the figures from Marquart *et al*[17] of 0.054 Wm^{-2} for ozone and -0.036 Wm^{-2} for methane over the same period. Results from Valks *et al*[39] indicate an RF due to ozone of between 0.019 and 0.037 Wm^{-2} in January and July 2015. Isaksen *et al*[15] predicted RF in 2015 due to ozone to be 0.047 Wm^{-2} , and that due to methane as -0.032 Wm^{-2}. Ponater *et al*[29] computed a global RF of between 0.0175 and 0.182 Wm^{-2} for ozone and between -0.0082 and -0.0856 Wm^{-2} for methane in 2050, indicating the significant level of variability in the simulations. These resulted in a global temperature change of between 0.0114 and 0.0764K due to ozone, and between -0.0046 and -0.039K for methane. Sausen *et al*[34] predicted a temperature change of between 0.010 and 0.097K for 2015 due to ozone using different scaling factors. The study of Rind *et al*[30] showed decreases in stratospheric ozone and increases in tropospheric ozone in 2005. Desssens *et al*[9] also looked at ozone effects using five different scenarios, with mixtures of subsonic and supersonic fleets. For the subsonic only case the ozone decrease was shown to cool the lower stratosphere by -1.6K at 22km over the North Pole. Bernsten *et al*[7] investigated tropospheric ozone and RF from 1900 to 1990, giving a global mean RF of 0.34 Wm^{-2} in 1990.

Fortuin *et al*[12] performed a global simulation up to 1990 using a radiative transfer model and showed an RF due to NO_2 of 0.003 Wm^{-2} in summer and -0.001 Wm^{-2} in winter. The RF due to ozone was between 0.034 and 0.135 Wm^{-2} in summer and 0.012 to 0.046 Wm^{-2} in winter, using a fixed temperature model assumption. Sausen *et al*[35] provided an updated estimate for 2000. Compared with IPCC results scaled to 2000, an RF due to ozone was 0.0129 Wm^{-2}, compared with 0.0289 Wm^{-2} using IPCC data. The methane RF also differed, the new results showed -0.0104 Wm^{-2} versus -0.0185 Wm^{-2} from scaled IPCC figures.

Forster *et al*[11] explored the suitability of using RFI as a metric for non-CO_2 effects of aviation. Their simulations for 1 to 500 years, with no growth in aviation, showed that the net GWP due to ozone and methane changes from 2.0 to -0.009×10^{-14} $Wm^{-2}kgCO_2^{-1}yr$. Fuglesvedt *et al*[13] showed sustained GWP due to NO_x to reduce from 1576 over 20 years, to 148 over 500 years. Johnson *et al*[16] investigated climate sensitivity to a step change of 1 Tg yr^{-1} in NO_x emissions. They reported an increase in RF due to ozone of 0.019594 Wm^{-2} in 10 years, and an overall step change in GWP of 456.0 after 100 years.

Pitari *et al*[24] investigated the effect of excluding or including sulphur emissions in a climate model, showing a difference of RF due to SO_4 from 0.00 to -0.007 Wm^{-2} . This induced changes in RF due to ozone from 0.027 to 0.015 Wm^{-2}, although no change in RF due to methane was seen (-0.008 Wm^{-2} in both cases). The effect of sulphate aerosol on RF was included in the predictions of Penner *et al*[1], giving -0.006 Wm^{-2} for 2015. This compares well to the results of Marquart *et al*[17] of -0.006 Wm^{-2} for 2015. The TRADEOFF estimates for sulphate aerosol RF effects in 2000 from Sausen *et al*[35] showed a slight reduction from those of IPCC (Penner *et al*[1] scaled to 2000, from -0.004 to -0.0035 Wm^{-2}. Danilin *et al*[8] performed aviation tracer fuel simulations for 1992 using 11 different global atmosphere models and concluded that the upper limit for RF due to sulphates is -0.013Wm^{-2}. The simulations of Fortuin *et al*[12] from 1943 to 1990 revealed an RF due to sulphate aerosol of between -0.182 and -0.550 Wm^{-2} for mid-latitude summer, and between -0.141 and -0.421 Wm^{-2} for mid-latitude winter, using a fixed temperature model assumption.

Soot can have a direct forcing effect on climate. The results of 11 global atmosphere models presented by Danilin *et al*[8] for 1992 data gave an RF due to soot of 0.006 Wm^{-2}. This compares with the value from Penner *et al*[1] of 0.003 Wm^{-2} for the same period. Sausen *et al*[35] estimated RF due to soot for 2000 to be 0.0025 Wm^{-2}, compared with 0.004 Wm^{-2} from the

IPCC data of Penner *et al*[1] scaled to 2000. Prediction of soot RF for 2015 were 0.006 Wm^{-2} from IPCC (Penner *et al*[1]), which compares well with the 0.006 Wm^{-2} result of Marquart *et al*[17].

Table 4 Overall effect of aviation on RF, GWP and temperature

<table>
<tr><th>Inputs – values and source</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Marquart *et al*., 2001 [17]

<table>
<tr><th>Model inputs</th><th>Kerosene</th><th>LH_2 (cryoplane)</th></tr>
<tr><td>Mass of equal energy</td><td>1kg</td><td>0.357kg</td></tr>
<tr><td>Emission index H_2O</td><td>1.26kg (H_2O)/kg(ke)</td><td>3.21kg ((H_2O)/kg(ke)</td></tr>
<tr><td>Emission index NO_x</td><td>12.6g (NO_2)/kg(ke)</td><td>1.1 to 5.0g (NO_2)/kg(ke)</td></tr>
<tr><td>Global fuel consumption</td><td>270.1 Tg(kerosene) yr^{-1}</td><td>96.4 Tg(H_2O) yr^{-1}</td></tr>
<tr><td>Global H_2O emissions</td><td>340.4 Tg(H_2O) yr^{-1}</td><td>868.0 Tg(H_2O) yr^{-1}</td></tr>
<tr><td>Global NO_x emissions</td><td>1.04 Tg(N) yr^{-1}</td><td>0.088 to 0.411 Tg(N) yr^{-1}</td></tr>
</table>

Emission properties above are for 2015 scenario

</td><td>

<table>
<tr><th></th><th>2015</th><th>2050</th><th>2100</th></tr>
<tr><td>Kerosene</td><td>0.111</td><td>0.132</td><td>0.137</td></tr>
<tr><td>Cryo</td><td>0.125 to 0.131</td><td>0.109 to 0.115</td><td>0.098 to 0.104</td></tr>
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Morris *et al*., 2003 [22]

Emissions for predicted 2015 subsonic fleet in 2015 come from Baughcum *et al*. (1988) emissions inventory.[41]

Emissions for projected fleet of 500 supersonic aircraft come from IPCC.[1]

</td><td>

<table>
<tr><th>Latitude</th><th>RF Winter</th><th>RF Summer</th></tr>
<tr><td>Subsonic aviation</td><td></td><td></td></tr>
<tr><td>54°N standard</td><td>0.002</td><td>-0.001</td></tr>
<tr><td>54°N extreme</td><td>0.008</td><td>0.002</td></tr>
<tr><td>82°N standard</td><td>0.004</td><td>-0.006</td></tr>
<tr><td>82°N extreme</td><td>0.012</td><td>-0.007</td></tr>
</table>

Standard case=monthly mean water vapour perturbation profile

Extreme case=monthly mean water vapour perturbation profile + 2 standard deviations

</td></tr>
</table>

Inputs – values and source	**RF (Wm^{-2}), unless otherwise stated**

Penner *et al*. 1999 [1]

Scenario	Description
Fa1	Reference scenario developed by ICAO Forecasting and Economic Support Group (FESG); midrange economic growth from IPCC (1992); technology for both improved fuel efficiency and NOx reduction
Fa2	Fa1 traffic scenario; technology with greater emphasis on NOx reduction, but slightly smaller fuel efficiency improvement
Fc1	FESG low-growth scenario; technology as for Fa1 scenario
Fe1	FESG high-growth scenario; technology as for Fa1 scenario
Eab	Traffic-growth scenario based on IS92a developed by Environmental Defence Fund (EDF); technology for very low NOx assumed
Edh	High traffic-growth EDF scenario; technology for very low NOx assumed

Total RF	1990	2000	2015	2025	2050
Fa1	0.048	0.071	0.114	0.137	0.193
Fa2	0.048	0.071	0.114	0.136	0.192
Fc1	0.048	0.071	0.114	0.118	0.129
Fe1	0.048	0.071	0.114	0.161	0.280
Eab	0.048	0.068	0.103	0.184	0.385
Edh	0.048	0.083	0.146	0.265	0.564

Global mean surface temp increase (K)	1990	2000	2015	2025	2050
Fa1	0.000	0.004	0.015	0.024	0.052
Fc1	0.000	0.004	0.015	0.023	0.039
Fe1	0.000	0.004	0.015	0.026	0.070
Eab	0.000	0.004	0.014	0.026	0.090
Edh	0.000	0.005	0.019	0.038	0.133

Pitari *et al*. 2002 [24]

Scenario 1 includes NO_x, H_2O and hydrocarbon emissions from aircraft

Scenario 2 includes NO_x, H_2O, hydrocarbon and sulphur emissions from aircraft

No input values given

Scenario	Net RF
1	0.018
2	0 (approximately)

<table>
<tr><th>Inputs – values and source</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>
Ponater <i>et al</i>., 2006 [29]
Ker – standard, purely kerosene aviation, calculated using IPCC inventories for 1940 to 2050;

cryo1 – technology transition begins in 2015, with EU taking the lead followed by North America in 2020 and S. America, Asia and Middle East in 2025. cryoplanes introduction starts with smallest planes, with long-range aircraft following about 10 years later;

cryo2 – assumes fast transition, starting with gradual world-wide transition of small and medium-sized aircraft in 2015 and of large aircraft in 2025. Scenario results in complete switch to hydrogen fuel by 2050;

cryo3 – starts with world-wide transition later (2020), but proceeds as fast as cryo2 towards the end of the period.
</td><td>
Global RF [W m^{-2}] for 2050
<table>
<tr><th></th><th>Kerosene (min, max)</th><th>Cryo1</th><th>Cryo2</th><th>Cryo3</th></tr>
<tr><td>Sum of global RF</td><td>0.128 (0.1023, 0.1570)</td><td>102.2 (83.2, 184.5)</td><td>90.4 (74.9, 143.4)</td><td>107.4 (87.3, 198.3)</td></tr>
</table>
Global temp change (mK) for 2050
<table>
<tr><th></th><th>kerosene</th><th>Cryo1</th><th>Cryo2</th><th>Cryo3</th></tr>
<tr><td>Sum of global temp change</td><td>0.0410 (0.0309, 0.0829)</td><td>0.0383 (0.0290, 0.0731)</td><td>0.0371 (0.0283, 0.0422)</td><td>0.0390 (0.0296, 0.0755)</td></tr>
</table>
</td></tr>
</table>

Inputs – values and source	**RF (Wm^{-2}), unless otherwise stated**

Sausen *et al*., 2000 [34]

Scenario	Description
R	Reference case: historical CO2 concentration until 1995, IS92a thereafter (all natural and anthropogenic sources including aircraft emissions).
Fa1	Standard aircraft emissions scenario: historic data (IEA) until 1995, NASA for 2015, FESGa (tech option 1) for 2050, 1% annual growth thereafter.
Fa2	As FA1, but for tech option 2
Fe1	Aircraft emissions scenario: historic data (IEA) until 1995, NASA for 2015, FESGe (tech option 1) for 2050*
Fc1	Aircraft emissions scenario: historic data (IEA) until 1995, NASA for 2015, FESGc (tech option 1) for 2050*
Eab	Aircraft emissions scenario: historic data (IEA) until 1995, EDFa-base thereafter
Eah	Aircraft emissions scenario: historic data (IEA) until 1995, EDFa-high thereafter
Cτ	As Fa1, but aircraft emissions constant for t ≥ τ.
N2015	As Fa1, but no aircraft emissions after 2015

* These two scenarios only run until 2050; others were run until 2100

Temperature change (K)

Year	R	Fc1	Fa1	Fe1	Eab	Eah	C_{1995}	C_{2015}	C_{2050}	N_{2015}
1950	0.232	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1970	0.305	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
1990	0.437	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
1992	0.455	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
1995	0.483	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
2000	0.532	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
2015	0.702	0.010	0.010	0.010	0.010	0.011	0.010	0.010	0.010	0.010
2050	1.230	0.023	0.025	0.028	0.033	0.050	0.018	0.024	0.025	0.015
2100	2.159		0.047		0.086	0.146	0.025	0.036	0.043	0.011

Sausen *et al*., 2005 [35]

New estimates of FR from a number of climate models, to update IPCC 1999 estimates for 2000. Scenarios: 1992 data scaled to 2000; IPCC 1999 data scaled to 2000; 2000 (TRADEOFF).

	1992 (IPCC, 1999)	2000 (IPCC, scaled to 2000)	2000 TRADEOFF
Total RF (Wm^{-2}) w/o cirrus	0.0485	0.0713	0.0478

Table 5 Effect of aviation’s CO_2 on RF, GWP and temperature

<table>
<tr><th>Inputs – values and source</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>Forster <i>et al</i>., 2006 [11]
Inputs assume an exponential increase in aviation emissions since 1950 to year 2000 of 150 TgC Growth follows the SRES A1B scenario (IPCC, 2000)</td><td>
<table>
<tr><th>Time horizon (2000 start), years</th><th>Absolute global warming potential due to CO_2 [10^{-14} W m^{-2} kg CO_2^{-1} yr]</th></tr>
<tr><td>1</td><td>0.5</td></tr>
<tr><td>20</td><td>2.65</td></tr>
<tr><td>100</td><td>9.15</td></tr>
<tr><td>500</td><td>29.9</td></tr>
</table>
</td></tr>
<tr><td>Fortuin <i>et al</i>., 1995 [12]
Aircraft-induced CO_2 enhancement from 1943 to 1990
Lower estimate: +1.25 ppmv
Upper estimate: +1.55 ppmv</td><td>
<table>
<tr><th></th><th colspan="2">Mid-latitude summer</th><th colspan="2">Mid-latitude winter</th></tr>
<tr><td>RF due to CO_2</td><td>Fixed temp</td><td>Fixed dynamical heating</td><td>Fixed temp</td><td>Fixed dynamical heating</td></tr>
<tr><td>Lower estimate</td><td>0.023</td><td>0.023</td><td>0.019</td><td>0.023</td></tr>
<tr><td>Upper estimate</td><td>0.029</td><td>0.028</td><td>0.018</td><td>0.022</td></tr>
</table>
</td></tr>
<tr><td>Johnson <i>et al</i>., 1996 [16]
Aircraft CO_2 emissions 500 Tg yr^{-1}</td><td>
<table>
<tr><th>Response to a 1 Tg yr^{-1} step-change in aircraft NO_x emissions</th><th>After 100 years</th></tr>
<tr><td>Overall step change GWP from aircraft CO_2</td><td>1.0</td></tr>
</table>
</td></tr>
</table>

Inputs – values and source	RF (Wm^{-2}), unless otherwise stated

Marquart *et al*., 2001 [17]

Model inputs	Kerosene	LH_2 (cryoplane)
Mass of equal energy	1kg	0.357kg
Emission index H_2O	1.26kg (H_2O)/kg(ke)	3.21kg ((H_2O)/kg(ke)
Emission index NO_x	12.6g (NO_2)/kg(ke)	1.1 to 5.0g (NO_2)/kg(ke)
Global fuel consumption	270.1 Tg(kerosene) yr^{-1}	96.4 Tg(H_2O) yr^{-1}
Global H_2O emissions	340.4 Tg(H_2O) yr^{-1}	868.0 Tg(H_2O) yr^{-1}
Global NO_x emissions	1.04 Tg(N) yr^{-1}	0.088 to 0.411 Tg(N) yr^{-1}

Emission properties above are for 2015 scenario

Total aircraft-induced RF due to CO_2

	2015	2050	2100
Kerosene	0.041	0.061	0.066
cryoplane	0.041	0.025	0.014

Penner *et al*. 1999 [1]

Scenario	Description
Fa1	Reference scenario developed by ICAO Forecasting and Economic Support Group (FESG); midrange economic growth from IPCC (1992); technology for both improved fuel efficiency and NOx reduction

RF due to CO_2	1990	2000	2015	2025	2050
Fa1	0.016	0.025	0.038	0.048	0.074

<table>
<tr><th>Inputs – values and source</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Ponater *et al*., 2006 [29]

Ker – standard, purely kerosene aviation, calculated using IPCC inventories for 1940 to 2050;

cryo1 – technology transition begins in 2015, with EU taking the lead followed by North America in 2020 and S. America, Asia and Middle East in 2025. cryoplanes introduction starts with smallest planes, with long-range aircraft following about 10 years later;

cryo2 – assumes fast transition, starting with gradual world-wide transition of small and medium-sized aircraft in 2015 and of large aircraft in 2025. Scenario results in complete switch to hydrogen fuel by 2050;

cryo3 – starts with world-wide transition later (2020), but proceeds as fast as cryo2 towards the end of the period.

</td><td>
<table>
<tr><th>Global RF [W m^{-2}] for 2050 caused by:</th><th>ker</th><th>Cryo1</th><th>Cryo2</th><th>Cryo3</th></tr>
<tr><td>CO_2</td><td>0.0729</td><td>0.0610</td><td>0.0563</td><td>0.0641</td></tr>
</table>
<table>
<tr><th>Global temp change (K) for 2050 caused by:</th><th>ker</th><th>Cryo1</th><th>Cryo2</th><th>Cryo3</th></tr>
<tr><td>CO_2</td><td>0.0206</td><td>0.0196</td><td>0.0192</td><td>0.0200</td></tr>
</table>
</td></tr>
<tr><td>

Sausen *et al*., 2005 [35]

New estimates of RF from a number of climate models, to update IPCC 1999 estimates for 2000. Scenarios: 1992 data scaled to 2000; IPCC 1999 data scaled to 2000; 2000 (TRADEOFF).

</td><td>
<table>
<tr><th>RF (Wm^{-2}) due to:</th><th>1992 (IPCC, 1999)</th><th>2000 (IPCC, 1999 scaled to 2000)</th><th>2000 TRADEOFF</th></tr>
<tr><td>CO_2</td><td>0.0180</td><td>0.0250</td><td>0.0253</td></tr>
</table>
</td></tr>
<tr><td>

Sausen *et al*., 2000 [34]

Fa1: standard aircraft emissions scenario: historic data (IEA) until 1995, NASA for 2015, FESGa (tech option 1) for 2050, 1% annual growth thereafter.

</td><td>
<table>
<tr><th>Year</th><th>Temperature change (K) since 1800 due to CO_2 for scenario Fa1</th><th>RF due to CO_2 for scenario Fa1</th></tr>
<tr><td>1990</td><td>0.003</td><td>0.021</td></tr>
<tr><td>1995</td><td>0.004</td><td>0.024</td></tr>
<tr><td>2000</td><td>0.006</td><td>0.029</td></tr>
<tr><td>2015</td><td>0.010</td><td>0.046</td></tr>
<tr><td>2050</td><td>0.024</td><td>0.068</td></tr>
<tr><td>2100</td><td>0.047</td><td>0.082</td></tr>
</table>
</td></tr>
</table>

Table 6 Effect of aviation's H_2O on RF, GWP and temperature

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>**Fortuin *et al.*, 1995** [12]
Aircraft-induced contrail enhancement from 1943 to 1990: 0.5% cloudiness
Aircraft-induced enhancement from 1943 to 1990 due to water vapour
Lower estimate: +0.076 ppmv
Upper estimate: +0.380 ppmv</td><td>
<table>
<tr><th></th><th>Mid-latitude summer</th><th></th><th>Mid-latitude winter</th><th></th></tr>
<tr><th>RF due to water vapour</th><th>Fixed temperature</th><th>Fixed dynamical heating</th><th>Fixed temperature</th><th>Fixed dynamical heating</th></tr>
<tr><td>Lower estimate</td><td>0.010</td><td>0.006</td><td>0.052</td><td>0.028</td></tr>
<tr><td>Upper estimate</td><td>0.048</td><td>0.023</td><td>0.241</td><td>0.131</td></tr>
</table>
</td></tr>
</table>

Study and inputs	RF (Wm^{-2}), unless otherwise stated

Gauss *et al*. 2003 [14]

Water vapour from ECMWF meteorological data; fuel consumption estimates from NASA 2015 inventories.

Model run	Description
H_2O-C1	Water vapour emitted by subsonic aircraft is at a lifetime of 5 days below the 400-hPa surface. Above 400hPa, no loss mechanisms are applied apart from transport.
H_2O-C2	Reference case. Estimates tropospheric lifetime of aircraft-emitted water vapour based on meteorological data from ECMWF for 1997.
H_2O-C2^{+1}	As H_2O-C2, but cruising altitude of subsonic cryoplanes enhanced by 1km.
H_2O-C2^{+2}	As H_2O-C2, but cruising altitude of subsonic cryoplanes enhanced by 2km.
H_2O-C2^{+3}	As H_2O-C2, but cruising altitude of subsonic cryoplanes enhanced by 3km.
H_2O-C3	Troposphere lifetime of 8.75 days is applied up to the tropopause level defined by NCEP reanalysis data instead of the CTM2 tropopause.
H_2O-C4	Deals with sensitivity to lifetime of aircraft emitted water vapour in the troposphere – set here to be 2 days below the CTM2 tropopause. *Nb sensitivity analysis rather than realistic simulation*
H_2O-C5	Estimates the significance of freezing and sedimentation of ice crystals.
H_2O-C6	Half of entire water vapour perturbation removed instantaneously if temperature below ice frost point.
H_2O-K1	Assesses the impact of subsonic kerosene aircraft
H_2O-K2	Assesses the impact of both subsonic and supersonic kerosene aircraft

Model run	Mean globally averaged RF at the tropopause
H_2O-C1	0.0098 (0.0036)
H_2O-C2	0.0065 (0.0020)
H_2O-C2^{+1}	0.0139 (0.0033)
H_2O-C2^{+2}	0.0297 (0.0052)
H_2O-C2^{+3}	0.0625 (0.0077)
H_2O-C3	0.0058 (0.0020)
H_2O-C4	0.0043 (0.0010)
H_2O-C5	0.0062 (0.0020)
H_2O-C6	0.0058 (0.0018)
H_2O-K1	0.0026 (0.0008)
H_2O-K2	0.0495 (0.0003)

Values in parentheses are the global averaged RF at the top of the atmosphere

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>
Marquart <i>et al</i>., 2001 [17]
<table>
<tr><th>Model inputs</th><th>Kerosene</th><th>LH_2 (cryoplane)</th></tr>
<tr><td>Mass of equal energy</td><td>1kg</td><td>0.357kg</td></tr>
<tr><td>Emission index H_2O</td><td>1.26kg (H_2O)/kg(ke)</td><td>3.21kg ((H_2O)/kg(ke)</td></tr>
<tr><td>Emission index NO_x</td><td>12.6g (NO_2)/kg(ke)</td><td>1.1 to 5.0g (NO_2)/kg(ke)</td></tr>
<tr><td>Global fuel consumption</td><td>270.1 Tg(kerosene) yr^{-1}</td><td>96.4 Tg(H_2O) yr^{-1}</td></tr>
<tr><td>Global H_2O emissions</td><td>340.4 Tg(H_2O) yr^{-1}</td><td>868.0 Tg(H_2O) yr^{-1}</td></tr>
<tr><td>Global NO_x emissions</td><td>1.04 Tg(N) yr^{-1}</td><td>0.088 to 0.411 Tg(N) yr^{-1}</td></tr>
</table>
Emission properties above are for 2015 scenario
</td><td>
<table>
<tr><th>Aircraft induced change in RF due to:</th><th>2015 kerosene</th><th>2015 cryoplane</th></tr>
<tr><td>H_2O</td><td>0.0008</td><td>0.0019</td></tr>
</table>
Results for 2050 and 2100 were identical to those for 2015 for these outcome measures.
</td></tr>
<tr><td>
Penner <i>et al</i>. 1999 [1]
Fa1: reference scenario developed by ICAO Forecasting and Economic Support Group (FESG); mid-range economic growth from IPCC (1992); technology for both improved fuel efficiency and NO_x reduction
</td><td>
RF due to H_2O
<table>
<tr><th>1990</th><th>2000</th><th>2015</th><th>2025</th><th>2050</th></tr>
<tr><td>0.002</td><td>0.002</td><td>0.003</td><td>0.003</td><td>0.004</td></tr>
</table>
</td></tr>
<tr><td>
Ponater <i>et al</i>., 2006 [29]
Ker – standard, purely kerosene aviation, calculated using IPCC inventories for 1940 to 2050;
cryo1 – technology transition begins in 2015, with EU taking the lead followed by North America in 2020 and S. America, Asia and Middle East in 2025. cryoplanes introduction starts with smallest planes, with long-range aircraft following about 10 years later;
cryo2 – assumes fast transition, starting with gradual world-wide transition of small and medium-sized aircraft in 2015 and of large aircraft in 2025. Scenario results in complete switch to hydrogen fuel by 2050;
cryo3 – starts with world-wide transition later (2020), but proceeds as fast as cryo2 towards the end of the period.
</td><td>
Global RF [W m^{-2}] for 2050 caused byH_2O
<table>
<tr><th>ker</th><th>Cryo1</th><th>Cryo2</th><th>Cryo3</th></tr>
<tr><td>0.0019 (0.0010, 0.0042)</td><td>0.0038 (0.0020, 0.0085)</td><td>0.0048 (0.0025, 0.0107)</td><td>0.0035 (0.0018, 0.0078)</td></tr>
</table>
Global temp change (K) for 2050 caused by H_2O
<table>
<tr><th>ker</th><th>Cryo1</th><th>Cryo2</th><th>Cryo3</th></tr>
<tr><td>0.0007 (0.0003, 0.0015)</td><td>0.0009 (0.0004, 0.0020)</td><td>0.0010 (0.0005, 0.0022)</td><td>0.0008 (0.0004, 0.0018)</td></tr>
</table>
</td></tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Ponater *et al*. 1996 [25]

Paper initially investigated enhanced water vapour emissions by factors of 10, 100, 1000 and 10000. There were no statistically significant changes for the factor 10 and 1000 scenarios, and the factor 1000 and 10000 scenarios were considered to be unrealistically extreme. Therefore, 3 additional sensitivity analyses were reported, with the high cloud cover (HCC) increased by 0.10, 0.05 and 0.02.

</td><td>
<table>
<tr><th>Global radiation (Wm^{-2}) JULY</th><th>Control experiment</th><th>Response to +0.10 increase in HCC</th><th>Response to +0.05 increase in HCC</th><th>Response to +0.02 increase in HCC</th></tr>
<tr><td>Top solar radiation</td><td>233.6 ± 0.5</td><td>-2.3</td><td>n/s</td><td>n/s</td></tr>
<tr><td>Top thermal radiation</td><td>-236.9 ± 0.5</td><td>+1.3</td><td>+0.7</td><td>n/s</td></tr>
<tr><td>Top net radiation</td><td>-3.4 ± 0.6</td><td>-1.0</td><td>n/s</td><td>n/s</td></tr>
<tr><td>Atmospheric solar radiation</td><td>65.7 ± 0.2</td><td>n/s</td><td>n/s</td><td>n/s</td></tr>
<tr><td>Atmospheric thermal radiation</td><td>-166.8 ± 0.6</td><td>n/s</td><td>n/s</td><td>n/s</td></tr>
<tr><td>Atmospheric net radiation</td><td>-101.1 ± 0.5</td><td>n/s</td><td>n/s</td><td>n/s</td></tr>
</table>
<table>
<tr><th>Global radiation (Wm^{-2}) JANUARY</th><th>Control experiment</th><th>Response to +0.10 increase in HCC</th><th>Response to +0.05 increase in HCC</th><th>Response to +0.02 increase in HCC</th></tr>
<tr><td>Top solar radiation</td><td>243.0 ± 0.8</td><td>n/s</td><td>n/s</td><td>n/s</td></tr>
<tr><td>Top thermal radiation</td><td>-227.6 ± 0.6</td><td>+1.3</td><td>n/s</td><td>n/s</td></tr>
<tr><td>Top net radiation</td><td>15.4 ± 0.5</td><td>n/s</td><td>n/s</td><td>n/s</td></tr>
<tr><td>Atmospheric solar radiation</td><td>72.5 ± 0.2</td><td>n/s</td><td>n/s</td><td>n/s</td></tr>
<tr><td>Atmospheric thermal radiation</td><td>-166.8 ± 0.5</td><td>n/s</td><td>n/s</td><td>n/s</td></tr>
<tr><td>Atmospheric net radiation</td><td>-94.2 ± 0.6</td><td>n/s</td><td>n/s</td><td>n/s</td></tr>
</table>
</td></tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>Ponater <i>et al</i>., 2005 [28]
Model of climate sensitivity parameter to contrail cirrus, using ECHAM4 global climate model with amendments for contrails and with a mixed layer ocean model.</td><td>Model results (single scenario)
Cirrus change (contrail coverage) 3.2%
Net RF 0.19 Wm^{-2} (0.29)*
Surface temperature response, 0.082 K
* value in parenthesis indicates a 25% increase in longwave RF for consistency with work by Marquart <i>et al</i>. (2003)[18]
The global climate sensitivity parameter to contrail cirrus was 0.43 $K(Wm^{-2})^{-1}$</td></tr>
<tr><td>Rind <i>et al</i>., 1996 [31]
<table>
<tr><th>Scenario</th><th>Water vapour input</th></tr>
<tr><td>1</td><td>1.17×10^{14} kg yr^{-1}</td></tr>
<tr><td>2</td><td>5.85×10^{12} kg yr^{-1}</td></tr>
<tr><td>3</td><td>5.85×10^{11} kg yr^{-1}</td></tr>
<tr><td>4</td><td>5.85×10^{10} kg yr^{-1}</td></tr>
</table>
Background water mass for control run with no aircraft emissions is 1.6×10^{16} kg; background water vapour mass at 12 km is approximately 1.2×10^{14} kg.</td><td>
<table>
<tr><th></th><th></th><th colspan="4">Change compared with control run</th></tr>
<tr><td></td><td>Control</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>Surface air temperature, °C</td><td>13.46</td><td>1.03</td><td>0.24</td><td>-0.07</td><td>0.07</td></tr>
<tr><td>Vertically integrated temperature, °C</td><td>-23.0</td><td>1.26</td><td>0.29</td><td>-0.07</td><td>0.08</td></tr>
</table></td></tr>
<tr><td>Sausen <i>et al</i>., 2005 [35]
New estimates of FR from a number of climate models, to update IPCC 1999 estimates for 2000. Scenarios: 1992 data scaled to 2000; IPCC 1999 data scaled to 2000; 2000 (TRADEOFF).</td><td>RF (Wm^{-2}) due H_2O
<table>
<tr><th>1992 (IPCC, 1999)</th><th>2000 (IPCC, 1999 scaled to 2000)</th><th>2000 TRADEOFF</th></tr>
<tr><td>0.0015</td><td>0.0020</td><td>0.0020</td></tr>
</table></td></tr>
</table>

Table 7 Effect of contrails on RF, GWP and temperature

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Fichter *et al*. 2005[10]

DLR-2 database and TRADEOFF emissions scenarios for different cruising altitudes

<table>
<tr><th>Scenario</th><th>Distance travelled ($\times 10^9$ km yr^{-1})</th></tr>
<tr><td>DLR2</td><td>18.0</td></tr>
<tr><td>TRADEOFF basecase</td><td>2.9</td></tr>
<tr><td>TRADEOFF+2kft</td><td>3.1</td></tr>
<tr><td>TRADEOFF-2kft</td><td>2.5</td></tr>
<tr><td>TRADEOFF-4kft</td><td>2.0</td></tr>
<tr><td>TRADEOFF-6kft</td><td>1.6</td></tr>
</table>

Kft=1000 feet

</td><td>

<table>
<tr><th>Scenario</th><th>Mean net RF by contrail forcing, based on distance travelled. Values in parenthesis represent best estimate for contrail RF</th></tr>
<tr><td>DLR2</td><td>2.1 (3.2)</td></tr>
<tr><td>TRADEOFF basecase</td><td>1.9 (2.9)</td></tr>
<tr><td>TRADEOFF+2kft</td><td>2.0 (3.1)</td></tr>
<tr><td>TRADEOFF-2kft</td><td>1.6 (2.5)</td></tr>
<tr><td>TRADEOFF-4kft</td><td>1.3 (2.0)</td></tr>
<tr><td>TRADEOFF-6kft</td><td>1.0 (1.6)</td></tr>
</table>

</td></tr>
<tr><td>

Forster *et al*., 2006 [11]

Inputs assume an exponential increase in aviation emissions since 1950 to year 2000 of 150 TgC Growth follows the SRES A1B scenario (IPCC, 2000)

</td><td>

<table>
<tr><th>Time horizon (2000 start), years</th><th>Absolute global warming potential due to contrails [10^{-14} W m^{-2} kg CO_2^{-1} yr]</th></tr>
<tr><td>1</td><td>6.7</td></tr>
<tr><td>20</td><td>6.7</td></tr>
<tr><td>100</td><td>6.7</td></tr>
<tr><td>500</td><td>6.7</td></tr>
</table>

</td></tr>
<tr><td>

Fortuin *et al*., 1995 [12]

Aircraft-induced contrail enhancement from 1943 to 1990: 0.5% cloudiness

Aircraft-induced enhancement from 1943 to 1990 due to water vapour

Lower estimate: +0.076 ppmv

Upper estimate: +0.380 ppmv

</td><td>

<table>
<tr><th>RF due to contrails</th><th>Mid-latitude summer</th><th>Mid-latitude winter</th></tr>
<tr><td>Lower estimate</td><td>-0.15</td><td>0.05</td></tr>
<tr><td>Upper estimate</td><td>0.3</td><td>0.3</td></tr>
</table>

Minimal and maximum forcing for an effective crystal radius. Fixed temperature model used

</td></tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Marquart *et al.*, 2001 [17]

<table>
<tr><th>Model inputs</th><th>Kerosene</th><th>LH_2 (cryoplane)</th></tr>
<tr><td>Mass of equal energy</td><td>1kg</td><td>0.357kg</td></tr>
<tr><td>Emission index H_2O</td><td>1.26kg (H_2O)/kg(ke)</td><td>3.21kg ((H_2O)/kg(ke)</td></tr>
<tr><td>Emission index NO_x</td><td>12.6g (NO_2)/kg(ke)</td><td>1.1 to 5.0g (NO_2)/kg(ke)</td></tr>
<tr><td>Global fuel consumption</td><td>270.1 Tg(kerosene) yr^{-1}</td><td>96.4 Tg(H_2O) yr^{-1}</td></tr>
<tr><td>Global H_2O emissions</td><td>340.4 Tg(H_2O) yr^{-1}</td><td>868.0 Tg(H_2O) yr^{-1}</td></tr>
<tr><td>Global NO_x emissions</td><td>1.04 Tg(N) yr^{-1}</td><td>0.088 to 0.411 Tg(N) yr^{-1}</td></tr>
</table>

Emission properties above are for 2015 scenario

</td><td>

Aircraft induced change in RF due to contrails

<table>
<tr><th>2015 kerosene</th><th>2015 cryoplane</th></tr>
<tr><td>0.052</td><td>0.081</td></tr>
</table>

Results for 2050 and 2100 were identical to those for 2015 for these outcome measures.

</td></tr>
<tr><td>

Marquart *et al.*, 2003 [18]

Parameterization of contrail formation for the ECHAM GCM. Fuel consumption data for 1992 and 2015 from DLR and Schmitt and Brunner 3D inventories [42]. Fuel consumption data for 2050 from NASA inventory (FESGa), Baughcum *et al*. 1998[41] and Penner *et al*. (1999) [1].

</td><td>

<table>
<tr><th>RF</th><th>1992</th><th>2015</th><th>2050</th></tr>
<tr><td>Longwave</td><td>0.0037
(0.0049)</td><td>0.0098
(0.0131)</td><td>0.0155
(0.0207)</td></tr>
<tr><td>Short wave</td><td>-0.0014</td><td>-0.0037</td><td>-0.0059</td></tr>
<tr><td>net</td><td>0.0023
(0.0035)</td><td>0.0061
(0.0094)</td><td>0.0096
(0.0148)</td></tr>
</table>

Values in parentheses are adjusted by a 25% offset to the longwave contrail radiative forcing.

Other results presented in paper, but only most likely scenarios included here (i.e. best estimate for propulsion efficiency increases, and model including climate change).

</td></tr>
</table>

Study and inputs | **RF (Wm^{-2}), unless otherwise stated**

Marquart *et al*., 2005 [19]

Model simulations assume contrail formation at 11km (247 hPa) altitude. Fuel consumption figures for 2015 are from DLR 3D inventory; those for 2050 are from NASA, scenario FESGa.

Global mean net RF	**2015**		**2050**	
Contrail particle properties	**conventional**	**cryoplane**	**conventional**	**cryoplane**
Non-spherical	0.0098 (0.0064)	0.0080 (0.0055)	0.0195 (0.0128)	0.0139 (0.0095)
Non-spherical, half size	0.0102 (0.0056)	0.0130 (0.0087)	NR	NR
Spherical, half size	0.0127 (0.0082)	NR	NR	NR

Values in parenthesis are original values calculated from ECHAM4 radiation scheme. Other values are the best estimate, and are adjusted by a 25% offset to the longwave global mean contrail RF.

Meerkötter *et al*. 1999 [20]

Inputs for the reference case:	
Ice water content	21 mg m^{-3}
Ice water path	4.4 g m^{-2}
Optical depth	0.52

At the top of the atmosphere, a mean contrail cover of 0.1% with average optical depth of 0.2 to 0.5 causes about 0.01 to 0.03 Wm^{-2} daily mean RF.

The authors note that values are uncertainty in contrail cover and optical depth values gives an uncertainty of factor 5 around these values.

Minnis *et al*., 1999 [21]

Global distribution of contrail cover computed for present meteorological conditions, a 1992 traffic database and an air traffic scenario of 2050. Contrail formation depends on the propulsion efficiency of the aircraft, assumed to be 0.3 for 1992 and for 2050. In the 2050 scenario, total aviation fuel consumption increases 3.2-fold compared to 1992 (4.4 for 500 hPa). Contrail cover expected to increase by a factor of 5 over present values.

Ice water content	**1992**	**2050**
0.1	0.008	0.049
0.3	0.017	0.099
0.5	0.020	0.122
Variable*	0.010	0.060

* variable ice water content calculated as a function of ambient temperature

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>
<p>Myhre <i>et al</i>. 2001 [23]</p>
<p>European Centre for Medium Range Weather Forecasts (ECMWF) for 1996 used for monthly mean global distribution of temperature, water vapour, clouds, and surface albedo.</p>
<p>Optical properties of hexagonal ice crystals for contrails are from Strauss <i>et al</i> (1997), with optical depth of 0.3 at 0.55µm. Altitude of the top of the contrails is 11km.</p>
<p>Distributions without diurnal variation were adopted from those by Sausen <i>et al</i> (1998), based on fuel consumption, moisture and temperature constrained to satellite observations of contrail cover. The annual mean contrail cover was used (0.09%).</p>
<p>Diurnal variation used the same data, but scaled using Schmitt and Brunner (1997) data on air traffic diurnal to infer a variation in the contrail cover.</p>
</td><td>
<table>
<tr><th>RF due to contrails for a 1% homogeneous contrail cover</th><th>Cloudy conditions</th><th>Clear conditions</th></tr>
<tr><td>Long wave RF</td><td>0.21</td><td>0.27</td></tr>
<tr><td>Short wave RF</td><td>-0.09</td><td>-0.15</td></tr>
<tr><td>Net RF</td><td>0.12</td><td>0.12</td></tr>
</table>
<table>
<tr><th>RF due to contrails for a realistic contrail cover</th><th>Diurnal cycle excluded</th><th>Diurnal cycle included</th><th>Maximum shortwave effect*</th></tr>
<tr><td>Long wave RF</td><td>0.020</td><td>0.020</td><td>0.020</td></tr>
<tr><td>Short wave RF</td><td>-0.009</td><td>-0.011</td><td>-0.020</td></tr>
<tr><td>Net RF</td><td>0.011</td><td>0.009</td><td>0.000</td></tr>
</table>
<p>*assumes that contrails occur at the time of day which maximizes the shortwave forcing.</p>
</td></tr>
<tr><td>
<p>Penner <i>et al</i>. 1999 [1]</p>
<p>Fa1: rreference scenario developed by ICAO Forecasting and Economic Support Group (FESG); mid-range economic growth from IPCC (1992); technology for both improved fuel efficiency and NO_x reduction</p>
</td><td>
<p>RF due to contrails</p>
<table>
<tr><th>1990</th><th>2000</th><th>2015</th><th>2025</th><th>2050</th></tr>
<tr><td>0.021</td><td>0.034</td><td>0.060</td><td>0.071</td><td>0.100</td></tr>
</table>
</td></tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Ponater *et al*., 2002 [27]

Radiative transfer and heating rates in the GCM were calculated using the radiation parameterization of Fouquart and Bonnel (1980) [43] and Morcrette (1991) [44] for the solar and terrestrial spectrum, respectively.

Sea surface temperature and sea ice extent in the reference experiment were prescribed by a mean annual cycle derived for the Atmospheric Model Intercomparison Project (AMIP) period 1979-1994.

The version 2 DLR aircraft emission data set used to calculate the actual contrail coverage from the potential coverage reflects the air traffic density distribution at the beginning of the 1990s.

</td><td>
<table>
<tr><th>Case</th><th>Stratosphere-adjusted net RF at the tropopause due to contrails</th></tr>
<tr><td>Reference experiment</td><td>0.2*</td></tr>
<tr><td>January</td><td>0.4</td></tr>
<tr><td>April</td><td>0.3</td></tr>
<tr><td>July</td><td>0.3</td></tr>
<tr><td>October</td><td>0.3</td></tr>
<tr><td>Annual mean</td><td>0.4</td></tr>
</table>

*instantaneous radiative forcing at top of the atmosphere

</td></tr>
<tr><td>

Ponater *et al*., 2006 [29]

Ker – standard, purely kerosene aviation, calculated using IPCC inventories for 1940 to 2050;

cryo1 – technology transition begins in 2015, with EU taking the lead followed by North America in 2020 and S. America, Asia and Middle East in 2025. cryoplanes introduction starts with smallest planes, with long-range aircraft following about 10 years later;

cryo2 – assumes fast transition, starting with gradual world-wide transition of small and medium-sized aircraft in 2015 and of large aircraft in 2025. Scenario results in complete switch to hydrogen fuel by 2050;

cryo3 – starts with world-wide transition later (2020), but proceeds as fast as cryo2 towards the end of the period.

</td><td>

Global RF [W m^{-2}] for 2050 caused by contrails

<table>
<tr><th>ker</th><th>Cryo1</th><th>Cryo2</th><th>Cryo3</th></tr>
<tr><td>0.0339 (0.0191, 0.0929)</td><td>0.0277 (0.0156, 0.0757)</td><td>0.0245 (0.0138, 0.0668)</td><td>0.0286 (0.0161, 0.0783)</td></tr>
</table>

Global temp change (K) for 2050 caused by contrails

<table>
<tr><th>ker</th><th>Cryo1</th><th>Cryo2</th><th>Cryo3</th></tr>
<tr><td>0.0056 (0.0032, 0.0153)</td><td>0.0053 (0.0030, 0.0144)</td><td>0.0051 (0.0029, 0.0140)</td><td>0.0053 (0.0030, 0.0146)</td></tr>
</table>

</td></tr>
<tr><td>

Sausen *et al*., 2005 [35]

New estimates of FR from a number of climate models, to update IPCC 1999 estimates for 2000. Scenarios: 1992 data scaled to 2000; IPCC 1999 data scaled to 2000; 2000 (TRADEOFF).

</td><td>

RF (Wm^{-2}) due to contrails

<table>
<tr><th>1992 (IPCC, 1999)</th><th>2000 (IPCC, 1999 scaled to 2000)</th><th>2000 TRADEOFF</th></tr>
<tr><td>0.0200</td><td>0.0339</td><td>0.0100</td></tr>
</table>

</td></tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>Strauss <i>et al</i>. 1997 [38]
Modelled outputs (July and October) from a 1D radiative convective model</td><td><table>
<tr><th></th><th>July</th><th>October</th></tr>
<tr><td>Surface temperature increases</td><td>1.1 K</td><td>0.8K</td></tr>
<tr><td>Increases in surface temperature, using an estimate of 0.5% of current cloud cover being due to contrails</td><td>0.06 K</td><td>0.05 K</td></tr>
</table></td></tr>
</table>

Table 8 Effect of aviation-induced cirrus clouds' effect on RF, GWP and temperature

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>
Rind <i>et al.</i>, 2000 [32]
<table>
<tr><th>Scenario</th><th>description</th></tr>
<tr><td>Control</td><td>CCI in the clear-sky hour after 200 clear-sky hours</td></tr>
<tr><td>1/200</td><td>CCI after 150 clear-sky hours</td></tr>
<tr><td>1/150</td><td>CCI after 100 clear-sky hours</td></tr>
<tr><td>1/100</td><td>CCI after 99 clear-sky hours</td></tr>
<tr><td>1/99</td><td>CCI for the 2 clear-sky hours after 98 clear-sky hours</td></tr>
<tr><td>1/98</td><td>CCI for the 3 clear-sky hours after 97 clear-sky hours</td></tr>
<tr><td>1/97</td><td>CCI for the 4 clear-sky hours after 96 clear-sky hours</td></tr>
<tr><td>1/96</td><td>CCI for the 5 clear-sky hours after 95 clear-sky hours</td></tr>
<tr><td>1/95</td><td>CCI varying between the insertion procedure for the 1/200 and 1/95 experiments, proportional to flight density</td></tr>
<tr><td>Scaled</td><td>CCI in the clear-sky hour after 200 clear-sky hours</td></tr>
</table>
CCI = cirrus cloud insertion
</td><td>
<table>
<tr><th>Scenario</th><th>Δ net radiation at top of model</th><th>Δ net radiation at tropopause</th><th>Δ initial surface temperature, °C</th><th>Δ equilibrium surface temperature, °C</th></tr>
<tr><td>1/150</td><td>-0.1</td><td>0 (0.1)</td><td>0.01</td><td>0.1</td></tr>
<tr><td>1/100</td><td>0</td><td>0.1 (0.19)</td><td>0.09</td><td>0.3</td></tr>
<tr><td>1/99</td><td>0.2</td><td>0.4 (0.49)</td><td>0.09</td><td>0.6</td></tr>
<tr><td>1/98</td><td>0</td><td>0.2 (0.18)</td><td>-0.02</td><td>0.6</td></tr>
<tr><td>1/97</td><td>0.6</td><td>0.8 (0.93)</td><td>0.13</td><td>1.1</td></tr>
<tr><td>1/96</td><td>0.9</td><td>1.2 (1.4)</td><td>0.21</td><td>1.4</td></tr>
<tr><td>1/95</td><td>1.3</td><td>1.8 (2.0)</td><td>0.23</td><td>1.7</td></tr>
<tr><td>Scaled</td><td>1.6</td><td>2.2 (2.4)</td><td>0.25</td><td>2.2</td></tr>
</table>
Nb, results were not presented for 1/20 run as it was reported to have been close to the control run.

Values in parentheses are corrected for the radiation imbalance for the initial temperature warming, since radiative forcing should be calculated without any temperature response and there was a small but non-zero response in these results.
</td></tr>
<tr><td>
Sausen <i>et al.</i>, 2005 [35]

New estimates of RR from a number of climate models, to update IPCC 1999 estimates for 2000. Scenarios: 1992 data scaled to 2000; IPCC 1999 data scaled to 2000; 2000 (TRADEOFF).
</td><td>
<table>
<tr><th>RF (Wm^{-2})</th><th>1992 (IPCC, 1999)</th><th>2000 (IPCC, 1999 scaled to 2000)</th><th>2000 TRADEOFF</th></tr>
<tr><td>Estimated mean for RF due to aviation-induced cirrus</td><td>-</td><td>-</td><td>0.030</td></tr>
<tr><td>Upper bound for RF due to aviation-induced cirrus</td><td>0.040</td><td></td><td>0.080</td></tr>
</table>
</td></tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>Stordal <i>et al</i>. 2005 [37]

Modelled cirrus cloud cover due to aircraft traffic, and calculations of radiative forcing due to aircraft using three different values for this relationship.</td><td>
<table>
<tr><th>Year 2000</th><th>Lower limit</th><th>Best estimate</th><th>Upper limit</th></tr>
<tr><td>Radiative impact of cirrus (Wm^{-2} per 1% cloud cover) and source</td><td>0.06 (Marquart <i>et al</i>. 2003)</td><td>0.12 (Myhre and Stordal, 2001)</td><td>0.20 (Boucher, 1999)</td></tr>
<tr><td>Calculated RF due to aircraft (Wm^{-2})</td><td>0.01</td><td>0.03</td><td>0.08</td></tr>
</table>
</td></tr>
<tr><td>Gauss <i>et al</i>. 2003 [14]

Water vapour from ECMWF meteorological data; fuel consumption estimates from NASA 2015 inventories.

See Table 6 for details of scenarios</td><td>
<table>
<tr><th>Model run</th><th>Mean globally averaged RF at the tropopause</th></tr>
<tr><td>H_2O-C1</td><td>0.0098 (0.0036)</td></tr>
<tr><td>H_2O-C2</td><td>0.0065 (0.0020)</td></tr>
<tr><td>H_2O-C2^{+1}</td><td>0.0139 (0.0033)</td></tr>
<tr><td>H_2O-C2^{+2}</td><td>0.0297 (0.0052)</td></tr>
<tr><td>H_2O-C2^{+3}</td><td>0.0625 (0.0077)</td></tr>
<tr><td>H_2O-C3</td><td>0.0058 (0.0020)</td></tr>
<tr><td>H_2O-C4</td><td>0.0043 (0.0010)</td></tr>
<tr><td>H_2O-C5</td><td>0.0062 (0.0020)</td></tr>
<tr><td>H_2O-C6</td><td>0.0058 (0.0018)</td></tr>
<tr><td>H_2O-K1</td><td>0.0026 (0.0008)</td></tr>
<tr><td>H_2O-K2</td><td>0.0495 (0.0003)</td></tr>
</table>
Values in parentheses are the global averaged RF at the top of the atmosphere</td></tr>
</table>

Table 9 Effects of ozone, NO_x and aerosols on RF, GWP and temperature

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Bernsten *et al*. 2000[7]

<table>
<tr><th>Date</th><th>Global NO_x emissions $Tg(N)yr^{-1}$</th></tr>
<tr><td>1990</td><td>36.5</td></tr>
</table>

NO_x emissions from aircraft set to 0 before 1950, to 5% of 1990 rate for 1950, and assuming an increase of 7.8% yr^{-1} from 1950 to 1990. 1990 data on NO_x emissions from aircraft came from DLR-2 database.

</td><td>

<table>
<tr><th>Date</th><th>Global mean RF</th></tr>
<tr><td>1990</td><td>0.34</td></tr>
</table>

</td></tr>
<tr><td>

Danilin *et al*., 1998 [8]

1992 subsonic fleet inventory from Baugchum *et al*, 1996 [41]. Four 2D and seven 3D global models used.

</td><td>

RF up to 0.006 due to soot emissions and -0.013 for sulphur emissions

</td></tr>
<tr><td>

Dessens *et al*. 2002 [9]

<table>
<tr><th></th><th>1995</th><th>2015</th></tr>
<tr><td>CO_2</td><td>353 ppmv</td><td>405 ppmv</td></tr>
<tr><td>N_2O</td><td>313 ppbv</td><td>335 ppbv</td></tr>
<tr><td>CH_4</td><td>1650 ppbv</td><td>1825 ppbv</td></tr>
</table>

5 scenarios: reference case (1995); predicted 2015 subsonic fleet (offline model); predicted 2015 subsonic fleet (online model); supersonic fleet added to subsonic fleet (offline model); supersonic fleet added to subsonic fleet (online model).

Temperature results in the paper were only presented for the online model.

</td><td>

<table>
<tr><th>Reference case</th><th>Online subsonic</th><th>Online super+subsonic</th></tr>
<tr><td>Troposphere warms, max of +1.5K in March. Stratosphere cools, reaching -10K at 25km. Ozone hole healing over the Antarctic in November leads to an increase in heating of the polar stratosphere (+6 K).</td><td>In the winter northern polar case with subsonic fleet emissions, ozone decrease cools lower stratosphere (-1.6K at 22km over the North Pole).</td><td>For both fleets, cooling in the Antarctic is seen in July (-3K for the supersonic case). In July NOx increase over northern hemisphere increases ozone, causing warming of 3K over North Pole.</td></tr>
</table>

</td></tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr>
<td>

Forster *et al*., 2006 [11]

Inputs assume an exponential increase in aviation emissions since 1950 to year 2000 of 150 TgC Growth follows the SRES A1B scenario (IPCC, 2000)

</td>
<td>
<table>
<tr><th>Time horizon (2000 start), years</th><th>NET absolute global warming potential due to CH_4 and O_3 [10^{-14} W m^{-2} kg CO_2^{-1} yr]</th></tr>
<tr><td>1</td><td>2.0</td></tr>
<tr><td>20</td><td>0.37</td></tr>
<tr><td>100</td><td>0.012</td></tr>
<tr><td>500</td><td>-0.009</td></tr>
</table>
</td>
</tr>
<tr>
<td>

Fortuin *et al*., 1995 [12]

Aircraft-induced enhancement from 1943 to 1990

<table>
<tr><th></th><th>Lower estimate</th><th>Upper estimate</th></tr>
<tr><td>Sulphate aerosol</td><td>+10%</td><td>+30%</td></tr>
<tr><td>NO_2</td><td>+20 pptv</td><td>n/a</td></tr>
<tr><td>O_3</td><td>+5 ppbv</td><td>+20 ppbv</td></tr>
</table>
</td>
<td>
<table>
<tr><th></th><th colspan="2">Mid-latitude summer</th><th colspan="2">Mid-latitude winter</th></tr>
<tr><th></th><th>Fixed temp</th><th>Fixed dyn. heating</th><th>Fixed temp</th><th>Fixed dyn. heating</th></tr>
<tr><td>RF due to sulphate aerosol</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Lower estimate</td><td>-0.182</td><td>-0.132</td><td>-0.141</td><td>-0.118</td></tr>
<tr><td>Upper estimate</td><td>-0.550</td><td>-0.401</td><td>-0.421</td><td>-0.352</td></tr>
<tr><td>RF due to NO_2</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Lower estimate</td><td>0.003</td><td>n/a</td><td>-0.001</td><td>n/a</td></tr>
<tr><td>Upper estimate</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td></tr>
<tr><td>RF due to O_3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Lower estimate</td><td>0.034</td><td>0.028</td><td>0.012</td><td>0.013</td></tr>
<tr><td>Upper estimate</td><td>0.135</td><td>0.111</td><td>0.046</td><td>0.050</td></tr>
</table>
</td>
</tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Fuglesvedt 1996 [13]

Baseline emissions data used unclear – *present day*.

Sustained step function increases in emissions used, from baseline: 1.1 to 1.7 times NO_x, and 1.1 to 2 times CH_4 and CO.

Figures for GWP from 1 to 500 years use 110% sustained step function increases.

</td><td>
<table>
<tr><th>Time horizon (years)</th><th>Sustained global warming potential due to aircraft NO_x</th><th>Sustained global warming potential due to aircraft CH_4 (direct)</th><th>Sustained global warming potential due to aircraft CH_4 (direct + indirect)</th></tr>
<tr><td>20</td><td>1576</td><td>35</td><td>63</td></tr>
<tr><td>50</td><td>751</td><td>24</td><td>44</td></tr>
<tr><td>100</td><td>441</td><td>16</td><td>30</td></tr>
<tr><td>200</td><td>268</td><td>10</td><td>19</td></tr>
<tr><td>500</td><td>148</td><td>2</td><td>1</td></tr>
</table>
</td></tr>
<tr><td>

Isaksen *et al*., 2001 [15]

<table>
<tr><th>Inputs</th><th>1992</th><th>2015</th><th>2050 medium</th><th>2050 high</th></tr>
<tr><td>NO_x emissions, $Tg(Nyr^{-1})$</td><td>0.5</td><td>1.27</td><td>2.17</td><td>3.46</td></tr>
<tr><td>Source of NO_x data</td><td>Current atmosphere</td><td>IPCC 1999</td><td colspan="2">IPCC 1999 – extrapolations of 2015 emissions*</td></tr>
<tr><td>CH_4 (ppbv)</td><td>1714</td><td>2052</td><td>2793</td><td></td></tr>
</table>

*options are for high or low growth in energy demand, and possibilities for technological improvements.

</td><td>
<table>
<tr><th>RF for aircraft emissions</th><th>1992</th><th>2015</th><th>2050</th><th>2050*</th></tr>
<tr><td>Methane</td><td>-0.015</td><td>-0.032</td><td>-0.053</td><td>NR</td></tr>
<tr><td>Ozone</td><td>0.020</td><td>0.047</td><td>0.077</td><td>0.068</td></tr>
</table>

These figures are relative to a model run with no aircraft emissions

* result for a model run where different regional growth rates between 1992 and 2050 in background emission are taken into account – rates not stated.

</td></tr>
</table>

Study and inputs	**RF (Wm^{-2}), unless otherwise stated**

Johnson *et al*., 1996 [16]

Aircraft NO_x emissions input: 2 Tg yr^{-1}

Response to a 1 Tg yr^{-1} step-change in aircraft NO_x emissions	**After 10 years**	**After 100 years**
RF forcing due to changes in ozone	19.594 mWm^{-2}	
Step change GWP for indirect radiative impact of methane		-32
Step change GWP for indirect radiative impact of tropospheric ozone		488
Overall step change GWP from aircraft NO_x		456.0
Overall step change GWP from aircraft CO_2		1.0

Marquart *et al*., 2001 [17]

Model inputs	**Kerosene**	**LH_2 (cryoplane)**
Mass of equal energy	1kg	0.357kg
Emission index H_2O	1.26kg (H_2O)/kg(ke)	3.21kg ((H_2O)/kg(ke)
Emission index NO_x	12.6g (NO_2)/kg(ke)	1.1 to 5.0g (NO_2)/kg(ke)
Global fuel consumption	270.1 Tg(kerosene) yr^{-1}	96.4 Tg(H_2O) yr^{-1}
Global H_2O emissions	340.4 Tg(H_2O) yr^{-1}	868.0 Tg(H_2O) yr^{-1}
Global NO_x emissions	1.04 Tg(N) yr^{-1}	0.088 to 0.411 Tg(N) yr^{-1}

Emission properties above are for 2015 scenario

Aircraft induced change in RF due to:	**2015 kerosene**	**2015 cryoplane**
O_3	0.054	0.005 to 0.021
CH_4	-0.036	-0.004 to -0.014
Sulphate aerosols	-0.006	*
soot	0.006	*

Results for 2050 and 2100 were identical to those for 2015 for these outcome measures.

* not given in paper, but assumed to be 0.

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Penner *et al*. 1999 [1]

Fa1= rreference scenario developed by ICAO Forecasting and Economic Support Group (FESG); mid-range economic growth from IPCC (1992); technology for both improved fuel efficiency and NO_x reduction

</td><td>
<table>
<tr><th>RF due to:</th><th>1990</th><th>2000</th><th>2015</th><th>2025</th><th>2050</th></tr>
<tr><td>O_3</td><td>0.024</td><td>0.029</td><td>0.040</td><td>0.046</td><td>0.060</td></tr>
<tr><td>CH_4</td><td>-0.015</td><td>-0.018</td><td>-0.027</td><td>-0.032</td><td>-0.045</td></tr>
<tr><td>Sulphate aerosol</td><td>-0.003</td><td>-0.004</td><td>-0.006</td><td>-0.007</td><td>-0.009</td></tr>
<tr><td>Soot (BC) aerosol</td><td>0.003</td><td>0.004</td><td>0.006</td><td>0.007</td><td>0.009</td></tr>
</table>
</td></tr>
<tr><td>

Pitari *et al* 2002 [24]

Scenario 1 includes NO_x, H_2O and hydrocarbon emissions from aircraft

Scenario 2 includes NO_x, H_2O, hydrocarbon and sulphur emissions from aircraft

No input values given

</td><td>
<table>
<tr><th>RF due to:</th><th>Scenario 1</th><th>Scenario 2</th></tr>
<tr><td>O_3</td><td>0.027</td><td>0.015</td></tr>
<tr><td>SO_4</td><td>0.00</td><td>-0.007</td></tr>
<tr><td>CH_4</td><td>-0.008</td><td>-0.008</td></tr>
</table>
</td></tr>
<tr><td>

Ponater *et al*. 1999 [26]

<table>
<tr><th colspan="2">1992 scenarios:</th></tr>
<tr><td>CTRL-92</td><td>Control run</td></tr>
<tr><td>1*MOG</td><td>Aircraft ozone from MOGUNTIA</td></tr>
<tr><td>2*MOG</td><td>Aircraft ozone from MOGUNTIA ×2</td></tr>
<tr><td>5*MOG</td><td>Aircraft ozone from MOGUNTIA ×5</td></tr>
<tr><td>equiv.CO_2</td><td>Aircraft ozone from MOGUNTIA, equivalent CO_2</td></tr>
<tr><td>ECH3-92</td><td>Aircraft ozone using Dameris *et al*[45]1992 scenario</td></tr>
<tr><td colspan="2">2015 scenarios:</td></tr>
<tr><td>CTRL-15</td><td>Control run, using background conditions predicted by IPCC scenario IS92a for 2015.</td></tr>
<tr><td>ECH3-15</td><td>Aircraft ozone using Dameris *et al*[45]1992 scenario</td></tr>
</table>

</td><td>
<table>
<tr><th>Scenario</th><th>RF</th><th>Annual mean [95% CI] surface air temperature (K)</th></tr>
<tr><td>CTRL-92</td><td>NR</td><td>NR (SD of monthly mean is 0.05)</td></tr>
<tr><td>1*MOG</td><td>0.068</td><td>0.096 [0.081, 0.111]</td></tr>
<tr><td>2*MOG</td><td>0.135</td><td>0.090 [0.075, 0.105]</td></tr>
<tr><td>5*MOG</td><td>0.331</td><td>0.728 [0.263, 0.293]</td></tr>
<tr><td>equiv.CO_2</td><td>0.069</td><td>0.061 [0.046, 0.076]</td></tr>
<tr><td>ECH3-92</td><td>0.031</td><td>0.062 [0.047, 0.077]</td></tr>
<tr><td>CTRL-15</td><td>NR</td><td>0.90</td></tr>
<tr><td>ECH3-15</td><td>NR</td><td>0.14</td></tr>
</table>
</td></tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Ponater *et al*., 2006 [29]

Ker – standard, purely kerosene aviation, calculated using IPCC inventories for 1940 to 2050;

cryo1 – technology transition begins in 2015, with EU taking the lead followed by North America in 2020 and S. America, Asia and Middle East in 2025. Cryoplanes introduction starts with smallest planes, with long-range aircraft following about 10 years later;

cryo2 – assumes fast transition, starting with gradual world-wide transition of small and medium-sized aircraft in 2015 and of large aircraft in 2025. Scenario results in complete switch to hydrogen fuel by 2050;

cryo3 – starts with world-wide transition later (2020), but proceeds as fast as cryo2 towards the end of the period.

</td><td>

Global RF [W m^{-2}] for 2050 caused by:

<table>
<tr><th></th><th>ker</th><th>Cryo1</th><th>Cryo2</th><th>Cryo3</th></tr>
<tr><td>O_3</td><td>0.0364 (0.0175, 0.1821)</td><td>0.0184 (0.0088, 0.0741)</td><td>0.0091 (0.0044, 0.0182)</td><td>0.0211 (0.0101, 0.0903)</td></tr>
<tr><td>CH_4</td><td>-0.0171 (-0.0082, -0.0856)</td><td>-0.0087 (-0.0042, -0.0348)</td><td>-0.0043 (-0.0021, -0.0086)</td><td>-0.0099 (-0.0048, -0.0422)</td></tr>
</table>

Global temp change (K) for 2050 caused by:

<table>
<tr><th></th><th>ker</th><th>Cryo1</th><th>Cryo2</th><th>Cryo3</th></tr>
<tr><td>O_3</td><td>0.0237 (0.0114, 0.0764)</td><td>0.0209 (0.0100, 0.0622)</td><td>0.0198 (0.0095, 0.0566)</td><td>0.0216 (0.0104, 0.0657)</td></tr>
<tr><td>CH_4</td><td>-0.0096 (-0.0046, -0.0309)</td><td>-0.0084 (-0.0040, -0.0251)</td><td>-0.0080 (-0.0038, -0.0229)</td><td>-0.0087 (-0.0042, -0.0266)</td></tr>
</table>

Values in parentheses indicate minimum and maximum values

</td></tr>
<tr><td>

Rind *et al*., 1995 [30]

GISS/CAM model investigates two scenarios of interest to the present study– ozone changes estimated from potential aircraft emissions by 2015, and more realistic water vapour changes from high-speed aircraft emissions.

</td><td>

Ozone changes for the year 2015 from aircraft emissions involve stratospheric ozone decreases and tropospheric ozone increases. The stratosphere generally cools, by up to 0.5°C. However, at the poles, stratospheric warming and mesospheric cooling of up to 2°C is experienced in the northern hemisphere.

With the stratospheric water vapour increase of 0.2ppmv by 2015 in the more realistic scenario, the stratosphere cools by 0.5°C or less, and regions of polar warming arise.

</td></tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>

Sausen *et al*., 1997[33]

Mean temperatures calculated by ECHAM4 GCM for different ozone scenarios, computed using 1× ozone change simulated by MOGUNTIA; 5×ozone change simulated by MOGUNTIA; 1× ozone change simulated by KNMI and 5× ozone change simulated by KNMI.

</td><td>

In July, each scenario's changed temperature exceeded the 90% significance level at least once. The 1×MOGUNTIA and 5×MOGUNTIA runs exceeded the 95% and 99% levels, respectively. In January, only the 1×MOGUNTIA and 5×MOGUNTIA scenarios produce significant signals.

The magnitude of the signal appears to depend nonlinearly on the magnitude of the ozone increase. The zonal mean temperature changes are in the range of ± 0.2K, which is about 5-10% of the response the same model simulates for doubling CO_2, in the upper troposphere. However, the signal due to the ozone changes is less coherent.

</td></tr>
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Sausen *et al*., 2000[34]

<table>
<tr><th>Scenario</th><th>Description</th></tr>
<tr><td>Fa1</td><td>Standard aircraft emissions scenario: historic data (IEA) until 1995, NASA for 2015, FESGa (tech option 1) for 2050, 1% annual growth thereafter.</td></tr>
<tr><td>Cτ</td><td>As Fa1, but aircraft emissions constant for t ≥ τ.</td></tr>
<tr><td>N2015</td><td>As Fa1, but no aircraft emissions after 2015</td></tr>
</table>

* These two scenarios only run until 2050; others were run until 2100

</td><td>

Temperature change (K) due to O_3

<table>
<tr><th></th><th>Fa1</th><th></th><th></th><th>C_{2015}</th><th>N_{2015}</th></tr>
<tr><th>Year</th><th>S=0.01</th><th>S=0.05</th><th>S=0.10</th><th>S=0.01</th><th>S=0.05</th></tr>
<tr><td>1995</td><td>0.005</td><td>0.023</td><td>0.045</td><td>0.005</td><td>0.023</td></tr>
<tr><td>2015</td><td>0.010</td><td>0.048</td><td>0.097</td><td>0.010</td><td>0.048</td></tr>
<tr><td>2050</td><td>0.022</td><td>0.111</td><td>0.221</td><td>0.022</td><td>0.111</td></tr>
<tr><td>2100</td><td>0.043</td><td>0.215</td><td>0.431</td><td>0.043</td><td>0.215</td></tr>
</table>

Scaling factor S is the equilibrium temperature response (in K) due to O_3 induced by aircraft NO_x emissions for 1992.

</td></tr>
<tr><td>

Sausen *et al*., 2005[35]

New estimates of FR from a number of climate models, to update IPCC 1999 estimates for 2000. Scenarios: 1992 data scaled to 2000; IPCC 1999 data scaled to 2000; 2000 (TRADEOFF).

</td><td>

<table>
<tr><th>RF (Wm^{-2}) due to:</th><th>1992 (IPCC, 1999)</th><th>2000 (IPCC, 1999 scaled to 2000)</th><th>2000 TRADEOFF</th></tr>
<tr><td>O_3</td><td>0.0230</td><td>0.0289</td><td>0.0219</td></tr>
<tr><td>CH_4</td><td>-0.0140</td><td>-0.0185</td><td>-0.0104</td></tr>
<tr><td>Direct sulphate</td><td>-0.0030</td><td>-0.0040</td><td>-0.0035</td></tr>
<tr><td>Direct soot</td><td>0.0030</td><td>0.0040</td><td>0.0025</td></tr>
</table>

</td></tr>
</table>

<table>
<tr><th>Study and inputs</th><th>RF (Wm^{-2}), unless otherwise stated</th></tr>
<tr><td>Stevenson <i>et al</i>., 2004 [36]
Model uses global annual mean emissions for 1990 to investigate 4 runs: control; NO_x increased by ×10 for January; NO_x increased by ×10 for April; NO_x increased by ×10 for July; NO_x increased by ×10 for October</td><td>
<table>
<tr><th>Run</th><th>Net RF mWm^{-2} yr^{-1}</th></tr>
<tr><td>January</td><td>-0.90</td></tr>
<tr><td>April</td><td>-0.89</td></tr>
<tr><td>July</td><td>-0.99</td></tr>
<tr><td>October</td><td>-0.89</td></tr>
<tr><td>Mean</td><td>-0.92</td></tr>
<tr><td>Lifetime corrected*</td><td>-0.95</td></tr>
</table>
</td></tr>
<tr><td>Valks <i>et al</i>., 1999 [39]
Calculation of RF due to ozone changes caused by NO_x from aircraft, with values of 0.55 Tg Ny^{-1} for 1990 and 1.06 Tg Ny^{-1} for 2015.</td><td>
RF due to ozone from aircraft NO_x
<table>
<tr><th>January 1990</th><th>July 1990</th><th>January 2015</th><th>July 2015</th></tr>
<tr><td>0.014</td><td>0.026</td><td>0.019</td><td>0.037</td></tr>
</table>
</td></tr>
<tr><td>Williams <i>et al</i>., 2002 [40]
Model of the effect of cruising altitude on the climate change impacts of aviation.</td><td>The model gave an annual mean increase in fuel burn of 3.9% for flying at restricted altitudes. The authors report that the initial impact of a 3.9% fuel burn increase on CO_2 RF by aviation would be less than 3.9% as the current forcing includes the impact of historic aviation emissions.</td></tr>
</table>

4.2.5 Summary of effects of aviation emissions

In this section 35 papers have been reviewed, describing the effect of aviation and its emissions on the environment and reporting RF, GWP and/or temperature changes as outputs. Upper and lower bounds for radiative forcing due to aviation studies aiming to provide plausible future scenarios, i.e. excluding artificial parameter study results, are shown in Table 10. Table 11 shows the percentage difference between lower and upper bounds for RF, to give an indication of the range of estimates for each contributing component. Summary results showing lower and upper bounds for surface temperature increase, relative to 1990, are shown in Table 13.

Predictions for overall RF due to aviation emissions for 2050 varied from 0.129 Wm^{-2} for a low-growth subsonic only case (*Fc1*), to 0.564 Wm^{-2} for a high growth scenario (*Edh*), with technology focus on low NO_x emissions (Penner *et al*[1]). More recent studies (Marquart *et al*[17] and Ponater *et al*[29]) reported RF in 2050 of between 0.128 and 0.132 Wm^{-2} respectively, compared with the mid-range *Fa1* scenario of 0.193 Wm^{-2} (Penner *et al*[29]). In Table 10, the lower bound for RF in 2050 is the lowest bound from Ponater *et al*[29], with the highest being that of the *Edh* high growth /low NOx technology scenario of Penner *et al*[1]. Table 11 shows that there is a difference between lower and upper bound of 149% and 142% for 2000 and 2015 respectively. The difference for 2050 of 551% reflects the large difference between the scenario used from Marquart et al[17], based on IPCC *Fa1*, and the highest emission *Edh* case from Penner *et al*[1]. The overall effect of aviation on surface temperature varies from between 0.004K and 0.005K for 2000, to between 0.039K and 0.133K in 2050, being highly dependent on the scenario in question.

The science around the direct effect of carbon dioxide on RF, GWP and temperature is established, with good correlation between RF due to carbon dioxide between Penner *et al* [1] and the more recent EU TRADEOFF project (Sausen *et al*[35]); 0.025 Wm^{-2} and 0.0253 Wm^{-2} respectively. The predicted result for 2050 is 0.074 Wm^{-2} (Penner *et al*[1]). Seasonal variation of RF due to carbon dioxide is also of importance (Fortuin *et al*[12]). The lower and upper bounds are those from the different growth and technology scenarios of Penner *et al*[1], and the more recent results of Sausen *et al*[34] for the IPCC *Fa1* scenario for 1990-2015. The lower bound for 2050 is provided by Marquart *et al*[17], for kerosene fuelled aircraft. The relatively small differences between lower and upper bound estimates in Table 11, and temperature effect in Table 13, are indicative of the higher level of confidence in modelling the effect of CO_2 on the global climate than other components.

Water vapour is a greenhouse gas, but its effect is minimal (Sausen *et al*[35], (Penner *et al*[1]) or not significant (Ponater *et al*[25], Rind *et al*[31]). The effect from cryoplanes is, however, more significant and dependent on cruising altitude (Marquart *et al*[17], Ponater *et al*[29], Gauss *et al*[14]). Modelling the direct effect of water on the climate is subject to significant variation, as indicated by the variations in Table 11, and the percentage variation of up to 420% in 2050 shown in Table 12. The difference in the modelled surface temperature effect is a factor of five higher for the upper versus lower bound, shown in Table 13.

Much of the current uncertainty around the effect of aviation on the climate is based around contrails and the indirect effect on cirrus cloud formation. The level of uncertainty around cirrus cloud effects is reflected in the exclusion of this from the IPCC reported overall RF figures (Penner *et al*[1]). More recently, a number of climate models were used to estimate the RF effect of cirrus clouds for 2000 to be between 0.030 and 0.080 Wm^{-2} (Sausen *et al*[35]), a difference of 800%. It has also been noted that global temperature responds linearly with high-level cloud cover (Rind *et al*[32]).

Prediction of RF due to contrails varies widely, from 0.0148 to 0.100 Wm^{-2} in 2050 (Marquart *et al*[19], Penner *et al*[1], Marquart *et al*[17], Ponater *et al*[29]) Variation in ice particle size assumptions results in large variations in calculated RF, from non-spherical particles inducing an RF of 0.0092 Wm^{-2} in 2050, versus 0.0127 Wm^{-2} for spherical, half-size particles (Marquart *et al*[46]).Variations in ice water content are also important (Minis *et al*[21], Meerkötter *et al*[20]). The latter paper stresses that the level of uncertainty over contrail RF is a factor of five, due to the lack of contrail cover and optical depth values. The balance of short wave and long wave RF contributions from contrail cover results in a net positive RF (Myhre *et al*[23]) which is reduced when the diurnal cycle is included. Variations in the lower and upper bound results, shown in Table 11, range from 340% for 2000, to 676% for 2050 estimates, with difference in surface temperature estimates for 2050 varying by 478%.

The effect of NO_x and methane on atmospheric ozone is a significant factor in climate dynamics with estimates for the RF due to ozone in 2050 ranging from 0.017 to 0.182 Wm^{-2} (Ponater *et al*[29]), a difference of over 1000%, with an associated temperature increase of between 0.0114 and 0.076K. The RF range for methane in 2050 is from -0.0082 to -0.0856 Wm^{-2} (Ponater *et al*[29], Marquart *et al*[17]), varying by over 1000%. These results indicate the high level of variability between simulations for ozone and methane effects.

The effect of sulphate aerosols is slight cooling on climate, with estimates for 2000 ranging from -0.0035 to -0.004 Wm^{-2} (Sausen *et al*[35]) and predictions for 2015 being -0.006 Wm^{-2}. It has also been shown that excluding sulphate chemistry from climate models can increase the RF due to ozone by over 55%, although no measurable effect on methane is detected (Pitari *et al*[24]).

Soot can have a forcing effect on climate, with RF estimates ranging from 0.003 to 0.006 Wm^{-2} for 1992 (Danilin *et al*[8], Penner *et al*[1]). Future predictions of soot effects for 2015 range from 0.004 Wm^{-2} for Penner et al[1] to 0.006Wm^{-2} from a different scenario in Penner *et al*[1] and Marquart *et al*[17]. Variation in the modelled effect of soot is over 150% for 200, 2015 and 2050.

Table 12 shows the contribution from aviation as an overall portion of global emissions for three different scenarios. The *A1F1* scenario [1] describes a future world of rapid economic growth, a peak of global population mid-century, followed a by a decline, and rapid introduction of new, efficient technologies, although remaining fossil-intensive. The *B1* scenario [1] has the same population growth profile as *A1F1*, but with reductions in material intensity, and introduction of clean, efficient technologies. The older *IS92a* scenario is included as reference [1]

It can be seen that in relation to both the *A1F1* and *B1* scenarios, aviation’s contribution to global radiative forcing remains between 3.59 and 5.34% for 2000, and 5.31% and 7.67% for 2015. The range for the predicted scenarios for 2050 becomes more significant, being as low as 2.12% for the *A1F1* scenario, and a worst case of 17.09% as the upper bound relative to the *B1* scenario. This demonstrates the difficulty in estimating future emissions on such large timescales, given the difficulty in estimating growth and technology trends, and the complex nature of the interactions between aviation emissions and the global climate.

Table 10. Lower and upper bounds for radiative forcing results

Effect	**Radiative Forcing due to aircraft, Wm^{-2}**							
	1990		**2000**		**2015**		**2050**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
CO_2	0.016[1]	0.021[34]	0.025[1]	0.029[34]	0.038[1]	0.046[34]	0.061[17]	0.074[1]
Water	0.002[1]	-	0.002[1;35]	-	0.0008[17]	0.003[1]	0.0010[29]	0.0042[29]
Contrails	0.021[1]	-	0.010[35]	0.034[1]	0.0102[19]	0.060[1]	0.0148[18]	0.100[1]
Cirrus	-	-	0.010[37]	0.080[35;37]	-	-	-	-
Ozone	0.024[1]	-	0.0219[35]	0.029[1]	0.04[1]	0.054[17]	0.017[29]	0.182[29]
NO_x	0.014[39]	0.026[39]	-	-	0.019[39]	0.037[39]	-	-
Methane	-0.015[1]	-	-0.0104[35]	-0.018[1]	-0.027[1]	-0.036[17]	-0.0082[29]	-0.0856[29]
Soot	-0.003[1]	-	0.0025[35]	0.004[1]	0.004[1]	0.006[1;17]	0.006[1;17]	0.009[1]
SO_x	-0.003[1]	-	-0.0035[35]	-0.004[1]	-0.006[1;17]	-	-0.007[1]	-
Overall	**0.048[1]**	**-**	**0.0478[35],**	**0.071[1]**	**0.103[1]**	**0.146[1]**	**0.1023[29]**	**0.564[1]**

Table 11. Percentage variation of radiative forcing results (high versus low bound)

Effect	**Percentage variation of radiative forcing results (high versus low bound)**			
	1990	**2000**	**2015**	**2050**
CO_2	131%	116%	121%	112%
Water	-	-	375%	420%
Contrails	-	340%	588%	676%
Cirrus	-	-	800%	-
Ozone	-	132%	135%	1071%
NO_x	186%	-	195%	-
Methane	-	173%	133%	1044%
Soot	-	160%	150%	150%
SO_x	-	114%	-	-
Overall	**-**	**149%**	**142%**	**551%**

Table 12. Aviation's contribution to global emissions

Effect	**Percentage of global radiative forcing**							
	1990		**2000**		**2015**		**2050**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
% global RF, A1F1 [1]	4.66%	-	3.59%	5.34%	5.34%[†]	7.56%[†]	2.12%	11.68%
% global RF, B1[1]	4.66%	-	3.59%	5.34%	5.31%[†]	7.67%[†]	3.10%	17.09%
% global RF, IS92a [1]	4.66%	-	3.65%	5.42%	5.67%[†]	8.04%[†]	3.15%	17.35%

[†] Based linearly interpolated value for global radiative forcing between 2010 and 2020.[1]

Table 13. Lower and upper bounds for surface temperature results

Effect	**Surface temperature increase since 1990 due to aircraft, K**							
	1990		**2000**		**2015**		**2050**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
CO_2	0	0	0.003[34]	-	0.007[34]	-	0.0206[29]	0.021[34]
Water	0	0	-	-	-	-	0.0003[29]	0.0015[29]
Contrails	0	0	-	-	-	-	0.0032[29]	0.0153[29]
Cirrus	0	0	-	-	-	-	-	-
Ozone	0	0	-	-	0.010[34]	0.097[34]	0.0114[29]	0.0764[29]
NO_x	0	0	-	-	-	-	-0.0046[29]	-0.0309[29]
Methane	0	0	-	-	-	-	-	-
Soot	0	0	-	-	-	-	-	-
SO_x	0	0	-	-	-	-	-	-
Overall	**0**	**0**	**0.004**[1]	**0.005**[1]	**0.015**[1]	**0.019**[1]	**0.039**[1]	**0.133**[1]

5 DISCUSSION

This study aimed to provide an overview of the current state of research into the effects of aviation on current and future climate. As outlined in Section 3, a systematic and objective search and data extraction strategy was developed and applied to research outputs from 1995 to 2007. Here we discuss the results presented in Section 4, assumptions and limitations of the approach, and suggestions for future research.

IPCC produced a comprehensive report on the effect of aviation on the environment in 1999[1]. The nature of IPCC is that it aims to include the research of significant scientific groups worldwide. The focus of this review was therefore to provide a picture of the current state of research in light of this major study in an objective way. The rapid increase in computational power, and hence simulation accuracy, scope and fidelity, has had a major effect on climate model research, meaning that more recent research may be seen as more relevant. Hence the timescale of 1995-2007 was chosen to be far enough before IPCC to include original research that was likely to be included, and bring this up to the present day. It is interesting to note that 25% of the studies pre-date the 1999 IPCC report.

The methodology aimed to identify the studies from which data were extracted in an objective and replicable manner. The criteria described in section 3.2 were developed *a priori* to include all types of aviation, and major global warming contributors with outcomes. The inclusion criteria were revised after an initial search, due to the large volume of references, to only include papers describing a climate model. This was justifiable as the focus of the research was to investigate future climate impact of aviation. Inclusion of papers that estimate existing and historical effects of aviation were included, as this is an important factor in determining the accuracy of climate models for predicting future behaviour. As one of the secondary outcomes of this research was to test the applicability of the systematic review methodology in this context, the revised inclusion criteria is considered pragmatic given the resources available. The advantage of the systematic search strategy was to minimise identification or selection bias, which is a risk of a less structured literature review approach.

The included articles were restricted to original research, including review articles that provided new interpretation of existing results. Many reports and articles in the public domain, such as the press, cite a limited number of sources. The aim was therefore to include original source material, rather than derivative work. Conference abstracts were searched for the last two years, as it was assumed that relevant research presented at conferences would appear within two years as published papers. The overall quality of the included papers was high, as discussed in Section 3.1, and primarily comprised peer-reviewed journal publications.

As discussed in Section 3.1, the papers were prioritised for data extraction so that some meaningful comparisons could be made of RF, GWP and temperature effects and due to limited resources to carry out the review. The priority B-D papers are listed in Appendix 4, and include recent studies that use, for instance, increases in carbon dioxide emissions as outcomes.

Two problems affecting review papers are reviewer and publication biases. Reviewer bias is minimised by using two independent reviewers who do not communicate when screening papers. Only if there is disagreement as to whether a paper should be included or excluded, is discussion entered into. While this doubles the resource requirement, which is significant in this case in which 579 papers were screened, it aims to ensure that bias is reduced.

Publication bias, also known as positive outcome bias, is the phenomenon of papers tending to only be published when a statistically significant result is achieved. This can be due to researchers not submitting papers in which results are not statistically significant, and/or journal editors tending to reject them for publication. In this case it is difficult to perform any analysis of publication bias. The IPCC report of Penner et al [1] can be seen as a meta-study, and is perhaps the only attempt to perform such a direct comparison in this particular context. No discussion of publication bias within the IPCC report is given, however. Restriction of the search to English language papers introduces a degree of publication bias, since much significant research is eventually published in the English language for international dissemination.

The results of the present review were considered in four groups, as dictated by the differences in model design, inputs and outcomes. The first set of papers reviewed was those which study the overall effect of aviation emissions on the climate. The IPCC report[1] provided a cross-comparison of several different climate models from different research groups. Two papers reported an update to the IPCC figures for 2000[34;35], using five different climate models, reflecting ongoing research to incorporate new scientific understanding and modelling. The only other works that studied overall effects were concerned with modelling the effect of hydrogen-powered cryoplanes. While not the focus of this study, they do report baseline cases for kerosene aircraft[17;29] and hence provide comparison with the other reports cited here. This supports the view that the IPCC report on aviation may be considered as comprehensive, and that its methodology and results are perhaps accepted by the research community.

Eight papers include extractable data on the effect of carbon dioxide from aviation on the atmosphere. These include the papers reporting overall effects[1;17;29;34;35], as CO_2 is the major climate driver. Fortuin *et al*[12] studied seasonal and latitudinal variation of CO_2 effects, which provides a more detailed breakdown of temporal and regional behaviour, for historical period 1943-1990. There is debate within the climate science community as to the validity of using Radiative Forcing Index[1] as an indicator for climate change, as there is no accounting for the differing timescales associated with greenhouse gases and their products. While it is useful as a single measure to show the equivalent effect of non-CO_2 emissions related to CO_2, it can be deemed over-simplistic when used to guide, for instance, changes in operational and design of aircraft. For example, when trading off the cumulative effect of CO_2 emissions versus the short-term effect of contrails. This is specifically tackled by Forster *et al*[11], who demonstrated that GWP may be a better metric when taking into account non- CO_2emissions on the environment. This is contrary to the discussion by Penner *et al*[1], who concluded that RFI is a better metric for aviation.

The majority of the papers surveyed (57%) were concerned with the effect of water, contrails and cirrus cloud cover on climate. This reflects the uncertainty in the science surrounding these factors, as highlighted by Penner *et al*[1]. The effect of water vapour, where isolated as a separate component, was shown to be an order of magnitude lower than that of carbon dioxide. The level of understanding regarding contrails and cirrus cloud formation, and how aviation emissions can affect these, is incomplete. This is reflected in the large variation in results from the studies reviewed, which can differ by an order of magnitude in RF for similar scenarios, or over 500% across the different studies reviewed here. The effect of cirrus clouds was excluded from the estimates given by IPCC in 1999[1], and there is still sufficient uncertainty to mean that it remains an active area of research. This is largely due to the complex physics and dependence on, for instance, contrail cover, and ice particle shape & size, which can lead to differences by a factor of five on RF [20]. It is only more recently that detailed contrail models have been incorporated into climate models [27], in an attempt to provide more accurate estimates. The importance of this topic is significant for the aircraft industry to guide mitigating strategies, such as changing cruising altitude or developing cryoplanes, that trade-off carbon dioxide emissions with water vapour, contrail and cirrus cloud impacts.

40% of the papers reviewed here were concerned with the effects of nitrogen oxides, sulphur oxides and aerosols from aviation on the climate. The chemistry related to these emissions is complex, as indirect effects due to their participation in ozone and methane chemistry must be considered. NO_x has a major influence on ozone chemistry, depending on altitude and temperature. It also affects the lifetime and concentration of methane. It is the nature, and modelling, of these indirect effects that provides scope for uncertainty. The effect of sulphur emissions is a net cooling effect, both directly and due to its on ozone and methane. The overall methane chemistry is complex, and for simulations to 2050, variations of over 1000% between studies is reported. As discussed above, the use of an RFI to account for both direct and indirect effects of non-CO_2 emissions is debatable[11], and GWP may be a better metric, although not without its own problems[1].

The systematic review methodology has been shown to provide an objective way of quantifying climate research, although meta-analysis remains difficult due to the nature and scope of the identified studies. It demonstrates the ongoing development of climate models to investigate and incorporate new science as understanding of physical processes improves, and computational resources allow more detailed simulations to be attempted. It highlights the focus of studies on the effect of NO_x, sulphates, contrails and cirrus cloud cover, showing how the community is trying to improve its knowledge and understanding of these complex topics. The priority B-D studies provide further detail of research in such areas, but do not provide RF, GWP and temperature as outcomes. The ongoing development of climate science is a necessary step in guiding the aerospace industry in the right direction to find sustainable solutions for the future.

6 CONCLUSIONS

In this study we have used the systematic review methodology to investigate the effect of aviation on global climate. An appropriate protocol was developed and applied by two independent reviewers, to identify research that met the inclusion criteria. These studies were prioritised and data extracted using a standard process. The 35 studies reviewed here reported radiative forcing, global warming potential and/or temperature changes as outcomes, allowing direct comparisons to be made.

Tabulated results and a narrative commentary were provided for overall effects on climate, and the individual effects of carbon dioxide, water, contrails, cirrus clouds, ozone, nitrogen oxides, methane, soot and sulphur oxides. Lower and upper bounds for these effects, and their relative contributions compared to overall radiative forcing and surface temperature changes, have been described.

This review shows that the most recent estimates for the contribution of aviation to global climate are highly dependent on the level of scientific understanding and modelling, and predicted scenarios for social and economic growth. Estimates for the future contribution of aviation to global radiative forcing in 2015 range from 5.31% to 8.04%. For 2050, the estimates have a wider spread, from 2.12% to 17.33%, the latter being for the most extreme technology and growth scenario. These global estimates should be considered within the context of uncertainties in accounting for the direct and indirect effects of different contributions. Variations between lower and upper bounds for estimates of radiative forcing are relatively low for carbon dioxide, around 131%, to 800% for cirrus clouds effects, and 1044% for soot. Advances in climate research, particularly in the area of contrail and cloud effects, has led to some revision of the 1999 IPCC estimates[1], and demonstrates that the research community is actively working to further understand the underlying science.

The approaches assumptions, limitations and future work were discussed in detail. We have demonstrated how the systematic review methodology can be applied to climate science, in a replicable and transparent manner.

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Appendix 1 - search strategy

The search strategy for Web of Science is given below.

Databases and years searched	**Date searched** **Strategy**
Web of Science ISI 1995-2007 English language	19/02/2007
	#1 20,608 TS=(aviation or aircraft or aeroplane* or airplane* or airline* or "air transport" or "air travel")
	#2 >100,000 TS=(metric* or model* or methodology or scenario* or index or calculation* or measurement or quantification* or quantify or forecast* or mulitplier* or "data collection" or "data assimilation" or "data analys?s")
	#3 >100,000 TS=(emission* or CO2 or "carbon dioxide" or "carbon equivalent" or NOx or "nitrogen oxide" or "nitrogen dioxide" or "cirrus cloud*" or contrail or methane or "sulphur oxide" or "sulfur oxide" or sulphates or sulfates or soot or particulates or "water vapo?r" or "radiative forcing" or "global warming" or "greenhouse gas" or atmosphere or stratosphere or troposphere)
	#4 **2,074** #1 and #2 and #3
Adding in climate as limit	#5 60,015 TS=(climate)
	#6 295 #4 and #5
Using terms in same field to increase specificity	#7 421 TS=(aircraft same emission*)
	#8 45 TS=(aviation same emission*)
	#9 0 TS=(aeroplane* same emission*)
	#10 5 TS=(airplane same emission*)
	#11 7 TS=("air transport*" same emission*)
	#12 7 TS=("air travel*" same emission*)
	#13 61 #8 or #10 or #11 or #12
	#14 447 #7 or #8 or #10 or #11 or #12
	#15 305 #2 and #14
	#16 82 #5 and #14
	#17 323 #15 or #16
	#18 554 #6 or #17
(19 - removing emission out of this line of strategy	#19 >100,000 TS=(CO2 or "carbon dioxide" or "carbon equivalent" or NOx or "nitrogen oxide" or "nitrogen dioxide" or "cirrus cloud*" or contrail or methane or "sulphur oxide" or "sulfur oxide" or sulphates or sulfates or soot or particulates or "water vapo?r" or "radiative forcing" or "global warming" or "greenhouse gas" or atmosphere or stratosphere or troposphere)
Climate+ generic aircraft emission + specific	#20 76 #5 and #14 and #19

Model etc + generic aircraft emission OR climate + generic emission OR climate + generic aircraft + specific	#21 **323** #15 or #16 or #20

Appendix 2 – Data extraction form

Reviewer:	Date:	Version:
Reference and Design	Model inputs	Outcome measures
Author *et al.*, year {refman ID} Geographical setting: Study design: Aviation type: Funding:	Parameters: Scenarios: 1. 2. 3.	Model outputs: Other climate outcomes: Method of assessing outcomes:

Model inputs and assumptions	Low	Medium	High
Model type			
Initial conditions			
Emissions			
CO_2			
water vapour			
NO_X			
particulates			
Climate drivers			
Growth rates			
Comments			

Outputs	Low	Medium	High
CO_2			
NO_X			
GWP			
Radiative forcing			
Effect on climate			
Comments			

Methodological comments Is the included study a journal paper, or was it a government/centre report? Does it appear to have been peer-reviewed? Who funded the study? Was the study consistent in reporting? (i.e. % or vol, global or local impact, current scenario or future implications)
General comments

Appendix 3 – Excluded studies

Many of the studies below were excluded for more than one reason, but for conciseness are listed under the prime exclusion criterion only.

Study type not meeting inclusion criteria:

Anable J, Lane B, Kelay T. An evidence base review of public attitudes to climate change and transport behaviour. Report for the Department of Transport. 2006.

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Systematic review of the impact of emissions from aviation on current and future climate

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