Project JETCLIM Final Report – Part A

Combining models of jet engine exhaust and climate impact to quantify the trade-offs of changes in engine design and aircraft operation

Main thematic area: Climate Change

Keith P Shine, Jolene Cook

University of Reading
March 2009

About Omega

Omega is a one-stop-shop providing impartial world-class academic expertise on the environmental issues facing aviation to the wider aviation sector, Government, NGOs and society as a whole. Its aim is independent knowledge transfer work and innovative solutions for a greener aviation future. Omega's areas of expertise include climate change, local air quality, noise, aircraft systems, aircraft operations, alternative fuels, demand and mitigation policies.

Omega draws together world-class research from nine major UK universities. It is led by Manchester Metropolitan University with Cambridge and Cranfield. Other partners are Leeds, Loughborough, Oxford, Reading, Sheffield and Southampton.

Launched in 2007, Omega (Omega=Opportunities for Meeting the Environmental Challenge of the Growth in Aviation) is funded by the Higher Education Funding Council for England (HEFCE)

www.omega.mmu.ac.uk

Report prepared by Keith P Shine and Jolene Cook	Principal Investigator: Professor Keith P Shine
Reviewed / checked by	Omega Office

Contents

Overall JETCLIM Executive Summary for Parts A and B

JETCLIM combined expertise in the climate impact of aviation emissions with expertise in aircraft and engine design. JETCLIM's purpose was to advance understanding of the climate impact of aviation and in particular to improve the assessment of the trade-offs that have to be considered, should changes in aircraft design or operation be contemplated.

Aviation emissions lead to a wide range of climate effects – CO_2, contrails and ozone changes (as a direct result of emissions of oxides of nitrogen (NO_x)) all have a warming influence. Decreases in methane, and an associated decrease in ozone, as an indirect result of emissions of NO_x, have a cooling influence. These climate effects can depend strongly on the height at which the emissions occur, and the persistence of the effects range from minutes to hours in the case of contrails, to around a decade for methane whilst a substantial proportion of the CO_2 perturbation persists for thousands of years.

This mixture of signs, height dependences and lifetimes of the climate effects makes it difficult to answer apparently simple questions such as "is it better to avoid forming contrails at the expense of emitting more carbon dioxide?" and "how would the climate influence of aviation change, if the fleet flew higher or lower?". The answers to such questions are further confounded by the fact that they depend on how the climate effect is defined and also on value-laden judgements on the timescale over which the climate effect is considered.

In JETCLIM, two important advances to an existing methodology, developed as part of the Airbus/DTI funded "Low Emissions Effect Aircraft" project, for assessing the height dependence of the climate effect of aviation emissions, were implemented. First, the representation of the climate influence of contrails was improved, by incorporating the way in which the properties (strictly the so-called ice water content) of the contrails depends on temperature. Secondly, a thermodynamic model of engine emissions was developed, which allows the computation of the dependence of fuel use (and hence CO_2 and NO_x emissions) on such factors as the size of the aircraft, the mission length and the Mach number. This allowed a much improved assessment of the effect of changes in cruise altitude on fuel use.

Results are presented for two different metrics of the climate impact of aviation emissions. The Global Warming Potential (GWP) (the time-integrated radiative forcing following a pulse emission of a gas) is a metric which has been adopted under the Kyoto Protocol to the United Nations Framework Convention on Climate Change as a means of converting emissions of non-CO_2 greenhouse gases to a CO_2-equivalent emission. The use of the GWP requires a value-laden choice of a time-horizon, and the Kyoto Protocol adopts 100 years (henceforth GWP(100)). A metric that has quite different properties is the Global Temperature Change Potential (GTP) which gives the temperature change (calculated using a simple climate model) at some time after a pulse emission – such a metric might be more applicable in the case of a climate policy which aims to keep warming below some given level. Its use also requires the choice of a time horizon. For longer time horizons, this metric tends to emphasize the role of long-lived emissions which, in the context of aviation, means CO_2.

The engine/airframe model is used to compute the configuration of an aircraft which minimises fuel-use (and hence CO_2 emissions and, approximately, NO_x emissions) for particular cruise altitudes. It is emphasized that if the present-day fleet is flown at heights other than the ones they were designed for, the penalty in fuel use would be significant.

The model shows that the minimum in fuel use, and hence in GWP(100) and GTP(100) for CO_2 occurs at around 35 kft, close to the cruise altitude of the present-day fleet. However, the two metrics give quite different views of the total climate impact, when the non-CO_2 influences are accounted for. In the case of the GWP(100), there is a local maximum for flights at around 35 kft, mostly because of the impact of contrails; for the GTP(100), there is a minimum at around the same altitude. This result stresses the importance of a careful choice of metric and time horizon which addresses the particular policy/technology question being posed.

Other results illustrate that the view of the altitude dependence of the GTP depends on the chosen time horizon. For short time horizons (10 and 20 years) the effect of the short-lived species is stronger and the climate effect has a local maximum for flights at around 35 kft. By contrast, at longer time horizons (50 and 100 years) the effect of CO_2 dominates, and there is a minimum at the same heights.

Other results illustrate the effect of other uncertainties – in particular, assumptions about the strength of the highly-uncertain aviation-induced cirrus forcing greatly affect the perceived height-dependence of the GWP (100), with results ranging from a very modest height dependence for flights below 40 kft, to a very strongly-peaked height dependence at 35 kft.

JETCLIM has advanced understanding of the height dependence of the climate effect of aviation, for aircraft that have been optimised to fly at particular heights. The methodology for calculating fuel use and the radiative forcing of contrails has been enhanced. The work has illustrated that there can be no definitive answer to the question of whether it is better to fly higher or fly lower. Firstly, the choice of metrics, and choices within those metrics (and in particular, the chosen time horizon) influence the perceived effects and choices will have to be made via consultations between scientists, policy makers and other interested stakeholders. Secondly, remaining uncertainties in climate science, and particularly the atmosphere's response to aviation emissions, can be severe and there is a need to lessen these uncertainties before authoritative answers can be given. Nevertheless, the techniques used in JETCLIM are advanced and could provide a basis for decision making.

1.0 Introduction

Aviation emissions lead to a wide range of climate effects, some tending to cause a warming, some tending to cause a cooling and many of which are highly dependent on the height at which the emissions occur. In addition, these climate effects have a wide range of lifetimes.

Contrails, formed as a result of water vapour emissions from aircraft, have lifetimes ranging from seconds to hours – their formation and persistence depends greatly on the prevailing atmospheric conditions. They are believed to have a warming influence on climate. Contrails can also spread into so-called aviation-induced cirrus, one of the most uncertain of the aviation-induced climate effects. Emissions of oxides of nitrogen (henceforth NO_x) lead to a wide range of climate impacts. At altitudes at which the current day fleet operates, NO_x leads to an increase in ozone abundance, which persists for timescales of days. The ozone change has a warming influence. However, the chemical reactions initiated by the NO_x emissions also lead to a reduction in methane abundance, which has a cooling influence. This is further enhanced by an associated decrease in ozone; these effects persist for timescales of decades. The final climate influence considered here is the effect of emissions of CO_2, which have a warming influence – a substantial fraction of any CO_2 emissions persist in the atmosphere for many thousands of years.

Hence, in assessing the climate impact of aviation, account has to be taken of the various influences, which vary in sign, size, lifetime and spatial distribution. Although the details of the science have moved on, the IPCC Special Report on Aviation (IPCC 1999) remains an excellent introduction to these issues. An up-to-date assessment of aviation led by D.S. Lee (MMU) and its impact on climate is due to be published in 2009 as part of the European Union funded "European Assessment of Transport Impacts on Climate Change and Ozone Depletion" (ATTICA) (www.pa.op.dlr.de/attica) – the ATTICA report will also include an assessment of climate metrics led by J.S. Fuglestvedt (CICERO, Oslo) and K.P. Shine (Reading).

JETCLIM was a collaborative project between the University of Reading and Cranfield University, with input from the University of Cambridge, which aimed to understand some of the trade-offs, from a climate perspective, in changes in engine design and operation. A particular focus of the study is the impact of changes in aircraft cruise altitude; changing the cruise altitude of an aircraft alters its propensity to form, and climate effect of contrails, and alters its fuel use, and hence its emissions of CO_2 and NO_x. The climate component of JETCLIM builds very heavily on the Airbus/DTI (now BERR) project LEEA ("Low Emissions Effect Aircraft"). Some of the main results of LEEA were reported in two papers: Köhler *et al.* (2008) discussed the height-dependent impact of NO_x emissions on ozone and radiative forcing; Rädel and Shine (2008) discussed the height-dependence of the contrail radiative forcing. A manuscript in preparation (Shine *et al.*) will use these two studies to present climate metrics which will indicate the impact of flying at different altitudes.

The innovation in JETCLIM focused on two areas. First, Cranfield University developed a new thermodynamic model of jet engine exhausts, which depended on a range of specifications of the aircraft type and operation; this provided information on the variation in fuel use (and hence CO_2 and NO_x) emissions with the aircraft and engine parameters, and in particular how these varied with aircraft cruise altitude. This is detailed in Part B of the JETCLIM final report (Poll, 2009). Second, the University of Reading enhanced the contrail radiative forcing model developed by Rädel and Shine (2008), to incorporate information on the way the opacity of contrails varies with the atmospheric temperature at cruise altitude. These innovations were then incorporated into a methodology, developed under LEEA, for deriving metrics for intercomparing the climate effect of aircraft flying at different cruise altitudes. This is detailed in this, Part A, of the JETCLIM final report.

A number of important caveats must be understood by readers of this report. Firstly, the discussion here focuses solely on the climate impact of changes in aircraft operation – there are, of course, wider environmental concerns about aircraft operations (including noise and air quality) and changes that may lower the climate impact of aviation do not necessarily decrease other environmental impacts. So, in addition to the climate trade-offs discussed here, there are wider environmental trade-offs that are beyond the scope of the present study.

Second, there are many uncertainties in the results presented here. These include fundamental scientific uncertainties in the impact of NO_x emissions and the properties and distribution of contrails, which limit the confidence in the results. Although the techniques employed here are considered state-of-the-art, it must be appreciated that results from different state-of-the-art models differ, sometimes considerably. Hence, there may be considerable volatility in the values presented here. A further difficulty is that the subject of providing climate metrics to intercompare different emissions from aircraft (which aim to put the emissions on some kind of common scale) is in its infancy – as will be shown, different metrics can provide distinctly different perceptions as to the dependence of the climate impact of aviation on cruise altitude. Scientists can provide values for these metrics, but the choice of metrics, and parameters within those metrics, are value-laden and must be made with consultation with policymakers and other stakeholders.

Finally, the work presented in this report has not yet undergone peer review, in the way that work published in the scientific and technical literature is required to do so. It is intended that this work will be submitted for publication in that literature, but it should be anticipated that changes to the results herein will be made as a normal consequence of that peer review.

1.0 Enhancement to the contrail radiative forcing model

One product of aviation that can be observed by the naked eye is the trail of condensation often left by jet engines. These contrails form when hot, humid exhaust gases are injected into cold, dry air and, thus, their formation is heavily dependent on atmospheric conditions, including temperature and saturation levels. The state of the surrounding environment also determines the properties of contrails that govern their radiative forcing, such as lifetime, vertical and horizontal spread and the shape of ice crystals, and as such, gives rise to a significant problem. These atmospheric conditions not only vary with altitude and geographical location, but may also undergo changes over short time and spatial scales, bringing with them the associated changes in contrail properties. This means that observing contrails for the purposes of investigating their impact on the climate is a particularly difficult task and, consequently, large uncertainties are inherent in our current knowledge of contrail radiative forcing.

Contrail radiative forcing is further complicated by the fact that contrails impose two competing effects on the Earth's energy system: firstly, they reflect incoming sunlight back out of the atmosphere, which leads to a cooling, and, secondly, they act to trap infrared energy in much the same way as greenhouse gases do, contributing a warming. The balance of these two impacts is a small net warming and the current estimate of the globally averaged forcing given by the latest IPCC assessment (Forster *et al.* 2007a) is around 0.01 Wm^{-2}. This value, however, is contained within reasonably large error bars ($\pm$0.02 Wm^{-2}) due to the uncertainties surrounding contrail properties, their location and the models used.

For this part of JETCLIM, we build on the work of Rädel and Shine (2008) to include a more realistic representation of persistent contrails in radiative forcing calculations. More specifically, we focus on contrail optical depth (at visible wavelengths), which is a measure of the opaqueness of a contrail. This is one of the most important factors affecting the climate impact of contrails, and it has been shown to scale linearly with radiative forcing, at least for plausible values of contrail optical depth.

1.1 The methodology

The basic methodology of this investigation is identical to that used by Rädel and Shine (2008). At the core of the investigation are calculations using the Fu and Liou radiative transfer model, which simulates the vertical transport of energy through the atmosphere. We use this model to determine the energy balance at the top of the atmosphere for a scenario in which contrails and natural clouds are present and compare the result with the energy balance for a control simulation in which contrails are removed. The difference is the radiative forcing due to contrails.

For this study, the interest lies in three inputs for the radiative transfer model: the contrail cover, that is, the percentage of the sky covered by contrails at different altitudes; the contrail optical depth; and the temperature of the environment surrounding a contrail. These are discussed in more detail below.

1.1.1 Derivation of the contrail cover

The contrail cover is based on actual air traffic data from the AERO2K flight inventory (www.cate.mmu.ac.uk/aero2k.asp), which provides the distance flown across the globe during 2002 plus the variation in traffic over a day for a week in June. The monthly totals of the distance flown at different altitudes are multiplied by the probability that the cold, ice-supersaturated conditions necessary for contrail formation are present to produce a three-dimensional contrail cover distribution. This information is derived from operational meteorological data provided by the European Centre for Medium Range Weather Forecasts (ECMWF). The global contrail cover distribution is then scaled to obtain a match with values from satellite observations from 1979 to 1981 and 1989 to 1992 for a region over Europe and the Atlantic (Bakan *et al.*, 1994). Finally, it is multiplied by a factor of two to account for an increase in air traffic over this specific area since those observations were made.

shows the derived distribution of contrail cover with peaks located over the Europe and North America relating to the high levels of air traffic across these areas. The globally-averaged contrail cover is 0.091% which is broadly consistent with estimates from other studies such as Sausen *et al.* (1998; 0.09%), Ponater *et al.* (2002; 0.07%) and Marquart *et al.* (2003; 0.06%), though it should be noted that all of these studies scale to the results of Bakan *et al.* (1994).

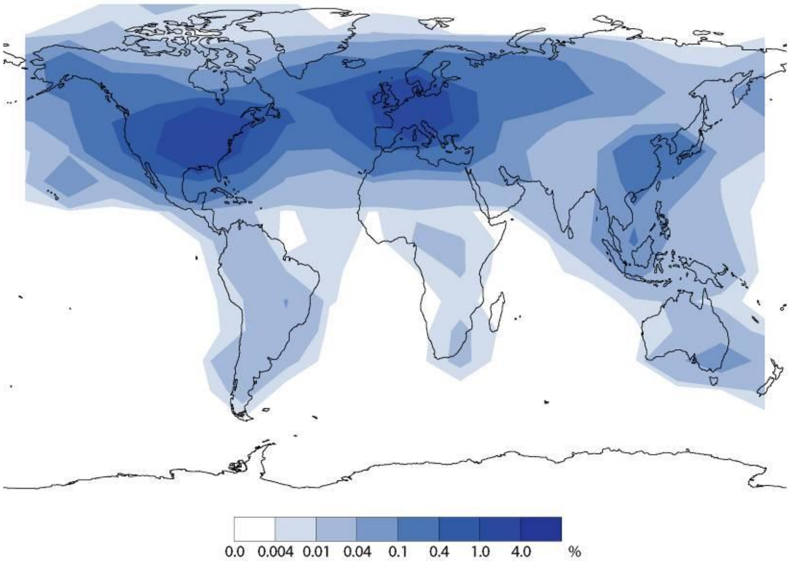

Figure 2.1: Contrail cover (%) derived from AERO2K air traffic data and atmospheric conditions for 2002

It is clear that significant uncertainties are introduced at this stage, including the assumptions regarding the seasonal and diurnal cycles of the air traffic data set itself. The application of a single scaling factor derived from one particular area to the entire globe is unlikely to be realistic. Checks have been made against regional contrail cover estimates for several other regions such as Thailand and Japan provided by Meyer *et al.* (2007) and reasonable agreement was found, but contrail cover requires further and more routine observation in order to increase our confidence. Fuller details of this procedure and the uncertainties are given in Rädel and Shine (2008).

1.1.2 Introducing variation of optical depth with location

Rädel and Shine (2008) used a simplified representation of contrails in the Fu and Liou radiative transfer model whereby the optical depth was fixed at a value of 0.15 regardless of the altitude or geographical location of the contrail. For the reasons discussed previously, measuring optical depth is difficult and, consequently, there are few estimates available in the current literature. A number of observational studies focus on specific regions; Minnis *et al.* (1999), for example, found optical depth over North America to be 0.3 from satellite observations, while Meyer *et al.* (2002) observed a mean value of 0.11 over Europe. Ponater *et al.* (2002) estimates that optical depth is less than 0.05 for Europe and between 0.04 and 0.25 for North America using model simulations. From these studies, it can be seen that estimates of optical depths vary significantly but there appears be some agreement between the model estimates and observations that it is higher over the US than over Europe. As for estimates of the global average, model results from Ponater *et al.* (2002) suggest a value of 0.15 at an altitude of 250hPa but some studies investigating contrail radiative forcing have chosen to use a higher value of 0.3 (e.g. Myhre and Stordal, 2001).

In this study, we introduce a more realistic representation of optical depth to our model that allows us to maintain the variation with altitude and geographical location seen in the literature. We draw on a parameterisation of contrail ice water content (IWC), a measure of the amount of ice water per unit volume which is linked to optical depth, based on the ambient temperature provided by Schumann (2002) – see Figure 2.2. This relationship is derived from a combination of both observations and model experiments, and shows that as temperature increases, IWC and, hence, optical depth increases. Thus, as the contrails are placed higher in the atmosphere, the drop in temperature that occurs as you go higher up into the troposphere leads to a lower IWC; on a horizontal plane, IWC values are larger closer to the warmer tropics. We assume here that when the ambient temperature is above -40°C, contrails are unable to form.

In order to link IWC to optical depth we require estimates of the vertical depth of the contrail. Again, this depends strongly on the environmental conditions such as wind, and is a very uncertain parameter. In the absence of this information, we choose to fix depth to a value of 400m for all contrails. This ensures that the global mean optical depth at 250hPa is set at 0.15 and is, therefore, consistent with the value from Ponater *et al.* (2002) and the value used by Rädel and Shine (2008). This depth is not unrealistic. It has been shown that after approximately 15 minutes, a contrail is able to extend to depths of 400 to 800m (Schumann 2002). It does, however, represent another major uncertainty in the calculation of the contrail radiative forcing. Had we chosen a depth of 800m, the global mean optical depth would have increased to 0.3, and our values of radiative forcing would have doubled.

Finally, it should also be noted that, while this parameterisation is an improvement on the fixed value of optical depth of Rädel and Shine (2008), the error bars attached to the individual points in Figure 2.2 are large, particularly considering the logarithmic vertical axis. These errors will filter through to the optical depth and, consequently, the calculation of the radiative effect.

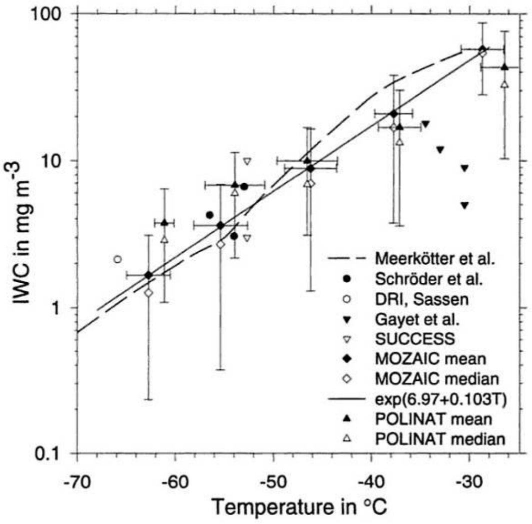

Figure 2.2: Relationship between contrail ice water content and ambient temperature. The solid line illustrates the parameterisation used in this study. Taken from Schumann (2002)

1.2 Contrail radiative forcing

Figure 2.3 shows the distribution of the net radiative forcing due to contrails when the new parameterisation of IWC is included to enable variable optical depths. A comparison with the results of Rädel and Shine (2008) shows that the pattern remains unchanged and the highest levels of radiative forcing still occur over Europe and North America. The magnitudes are reduced, however, and the global-mean net radiative forcing for this study is 4.2 mWm^{-2}, compared with 5.9mWm^{-2} of Rädel and Shine (2008).

We have also updated the results of Rädel and Shine (2008) with regard to the the sensitivity of radiative forcing to the altitude of the contrail. The total distance flown is increased by 10% within each 2000 ft vertical layer of the atmosphere in turn, and the global mean radiative forcing was compared with the the base experiment above. The impact of this increased traffic, and consequently, increased contrail cover, is shown in

Figure 2.4. When normalised to the global net forcing of the base experiment (Figure 2.4, left), the vertical profile of the impact on radiative forcing is broadly identical to the earlier study. Sensitivity to contrail altitude remains at its greatest around 10 km, approximately the cruise altitude of the current fleet, and drops steeply for altitudes above and below. When the distance flown within each layer is accounted for, however, the new parameterisation reduces the change in forcing above 8 km by up to 50% (
Figure 2.4, right), while below there is an increase.

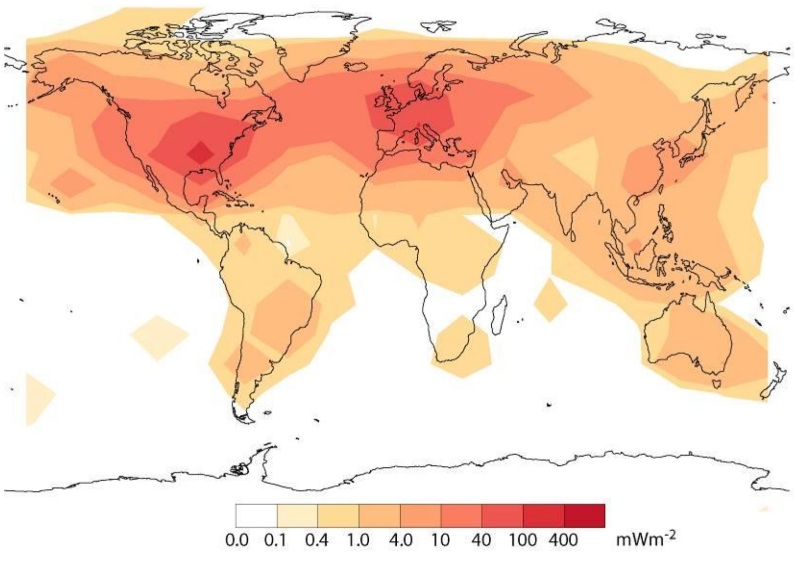

Figure 2.3: The distribution of all-sky net radiative forcing (mWm^{-2}) due to contrails including the new parameterisation of contrail ice water content

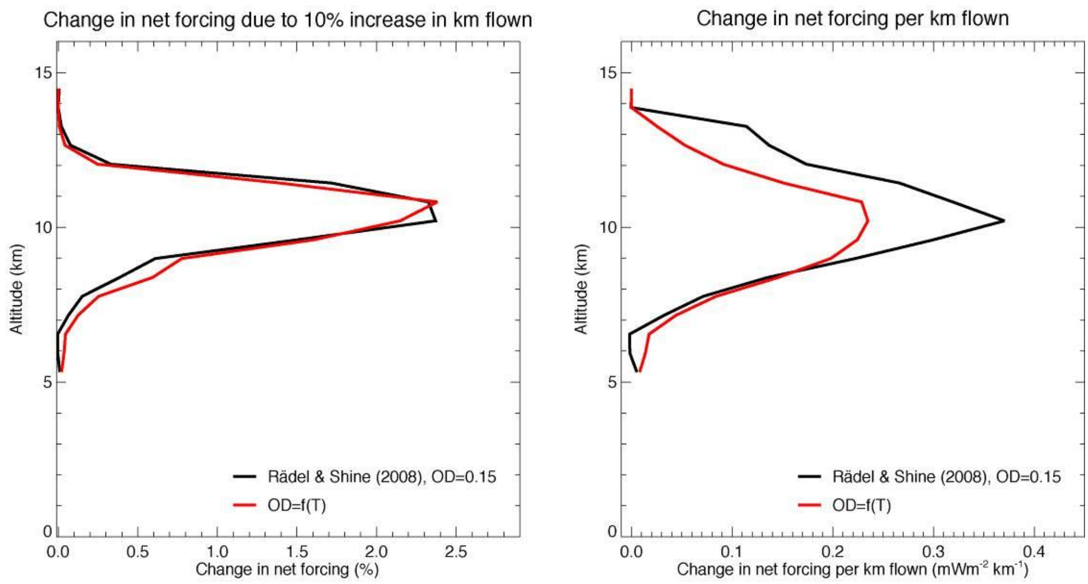

Figure 2.4: Change in the net forcing due to a 10% increase in the distance flown at each altitude: (left) the change normalised to the global mean forcing of the base experiment (%); and (right) the change per kilometre flown in 2002 within each 2000 ft thick atmospheric band (mWm^{-2} km^{-1} year)

1.3 Summary

In this part of the project we linked contrail optical depths to the temperature of the surrounding environment via ice water content, significantly improving the representation of contrails in radiative forcing calculations. Qualitatively, there is no change to the main results of Rädel and Shine (2008). Contrail radiative forcing is greatest over Europe and North America, and remains most sensitive to contrails at around 10km due to ideal atmospheric conditions for formation at this altitude.

Quantitatively, the forcing is reduced in magnitude when optical depth is allowed to vary with altitude and geographical location but it is essential that the uncertainties regarding the contrail cover and optical depth be borne in mind. In particular, while the variation of optical depth with altitude and location are more realistic, the choice of contrail depth and the errors attached to the IWC parameterisation lead to considerable uncertainties in the values of optical depth, and hence the radiative forcing, that we obtain.

2.0 Climate metrics

2.1 Basic concepts

This section will use the innovations described in the Section 2 and Part B (Poll 2009) and work previously developed under the LEAA project (see introduction) to illustrate the dependence on cruise altitude of the climate impact of aviation.

As noted in the introduction, aircraft emissions have widely different characteristics in terms of the way they influence climate and in the lifetime of these influences. To compare these emissions, it is necessary to put the emissions on some kind of common scale, for example to give them each a "CO_2 equivalence". It is, of course, desirable that any CO_2-equivalent emission, no matter what its detailed composition, would have the same climate impact, but in practice this is not possible to achieve. In addition, in the choice of climate metrics, and in the choices within any particular climate metrics, a number of value-laden decisions have to be made, which go beyond those which climate scientists can make – if such metrics are used in some legislative framework, ultimately it is policymakers who need to make these decisions. A comprehensive review of climate metrics which discusses many of these issues can be found in Fuglestvedt *et al.* (2003); other discussions can be found, for example, in Forster *et al.* (2006, 2007a and b) and Shine *et al.* (2007). The forthcoming ATTICA report (see introduction) will also include a review of climate metrics.

Results for two different types of climate metrics are presented here. The first is the (pulse) Global Warming Potential (GWP) – this represents the integrated radiative forcing due to a pulse emission of a species that can impact the climate. The integration is performed over some given time period ("time horizon"). This is the metric adopted by the Kyoto Protocol to the UN Framework Convention on Climate Change to place emissions of greenhouse gases other than CO_2 on a common CO_2-equivalent scale. It is thus widely used and simple to implement. The Kyoto Protocol chose a time horizon of 100 years, although IPCC reports (e.g. Forster *et al.* 2007a) present results for time horizons of 20, 100 and 500 years.

The second metric is the pulse Global Temperature Change Potential (PGTP) (Shine *et al.* 2007). The "end-point" is an estimate of the surface temperature change at some time after the pulse emission; it is quite distinct from the GWP in that it uses a different climate parameter (surface temperature change versus radiative forcing) and end-point (temperature change at a particular time versus integrated over some period of time). As discussed in Shine *et al.* (2007), and references therein, one attraction of the PGTP is that is may be better suited to target-based climate policies, such as the European Union's aim to restrict global warming to less than 2 °C above pre-industrial levels.

As will be seen, the GWP and PGTP perspectives can give quite different views of the climate impact of aviation and this encourages the user to consider the perspective that is most suited to their needs. It is possible to formulate sustained-emission versions of both the GWP and GTP concepts – see Berntsen *et al.* (2005) and Shine *et al.* (2005) respectively. The results for the sustained GTP and sustained GWP are very similar in form to those for the pulse GWP and so are not presented here.

The GWP and PGTP results are often presented as ratios to the effect of emitting CO_2 rather than as absolute values. However, in this work, the absolute value of the metrics are presented on a per km flown basis – the reason for this choice is that the dependence of CO_2 emissions with cruise altitude is then made explicit.

Finally, the adoption of the GTP requires the use of some physical model that relates the radiative forcing to surface temperature change – the model adopted here is a simple analytical model (see Shine *et al.* 2005); Shine *et al.* (2007) and Reddy and Boucher (2008) present results using a somewhat more sophisticated model, which tends to enhance the perceived importance of short-lived species. A further choice that is necessary in any climate model, is the specification of the so-called climate sensitivity parameter – this measures the (equilibrium) surface temperature change to a unit radiative forcing – there is chronic uncertainty in the actual value of this parameter (see e.g. IPCC 2007) – the default value used here is 0.8 $K(Wm^{-2})^{-1}$ although we will present some illustrations of the dependence of the results on this choice.

As stressed in the Introduction, the results reported here have yet to undergo peer review and should thus be considered preliminary until they have done.

The following sub-sections will present a selection of results from the methodology. Each plot will show the chosen metric as a function of aircraft cruise altitude – following the convention within the aviation industry, the vertical co-ordinate is thousands of feet (kft) – this can, of course, be approximately converted to kilometres by dividing by three.

2.2 Basic results

Figure 3.1 shows the basic format of the results using the original LEEA methodology. The metric values are derived using the radiative forcings presented in Köhler *et al.* (2008) and Rädel and Shine (2008). These results assume a geographical and height dependence of emissions following that of the present day fleet (strictly 2002) using the AERO2K database. The GWP and PGTP for 100 years time horizon (henceforth GWP(100) and PGTP(100)) are shown as a function of cruise altitude. The coloured lines show the individual contributions to the total metric – hence the NO_x emissions lead to a short-lived ozone forcing which leads to a positive value of the metric (blue solid curve); the NO_x also leads to a loss of methane, leading to a negative value (blue dashed curve) which in turn leads to a longer-lived loss of ozone (green curve). Contrails (yellow) lead to a positive value of the metrics – to account for uncertainties in the role of aviation induced cirrus (see introduction), the basic contrail forcings are multiplied by a factor of 5; the effect of this assumption will be discussed in a later section. The impact of CO_2 is shown in red, and here it is assumed that fuel use is simply proportional to air density. The total impact is shown by the black line.

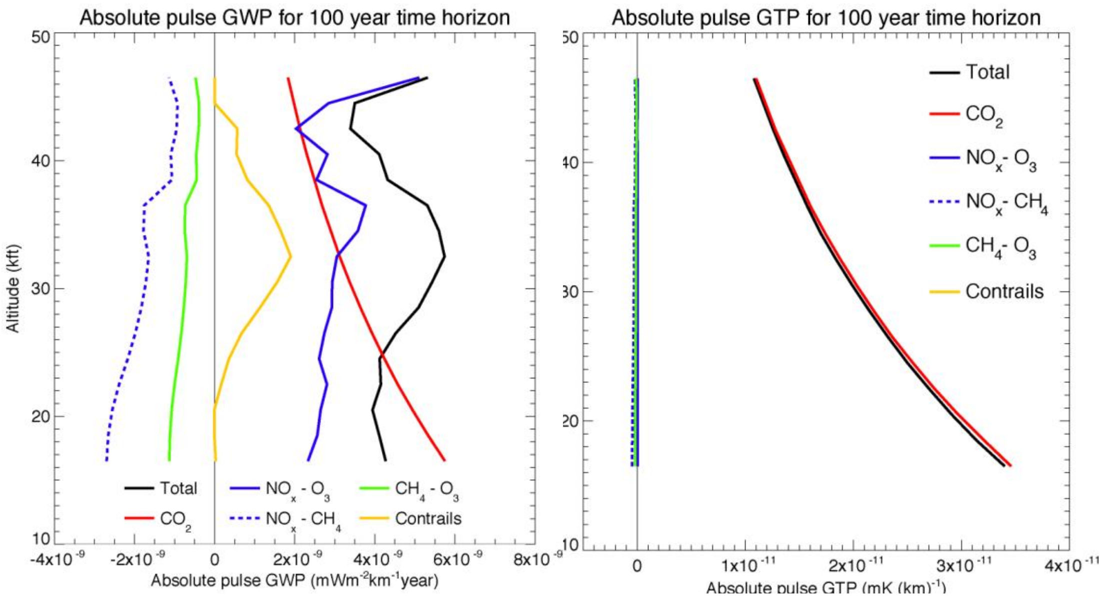

Figure 3.1: (Left) GWP and (Right) PGTP for the original LEEA model assuming a 100 year time horizon for each as a function of cruise altitude. The coloured curves show the individual contributions of the emissions, the black line shows the total effect. ***These results should be considered preliminary and are subject to change following peer review.***

Figure 3.1 (left) for the GWP(100), indicates broadly that aircraft flying at about 32 kft have the largest climate effect – the climate effect would decrease if the cruise altitude was lower. Note that, as discussed in Köhler *et al.* (2008), some of the structure in the metrics above 38 kft can be considered an "artefact" of the changing geographical distribution of aircraft in the AERO2K database at these heights, and the minimum at 43 kft is somewhat exaggerated. By contrast Figure 3.1 (right) for the GTP(100) shows almost complete dominance of CO_2. The reason is that the surface temperature impact of a pulse emission of the short-lived effects (contrails and NO_x) decays to almost nothing after 100 years, unlike CO_2 for which a significant component remains in the atmosphere for many thousands of years. Because the GWP(100) integrates the radiative forcing over time, the "memory" of these short-lived emissions is retained for longer in this metric, even if the emission is no longer having any climate impact.

2.3 Incorporation of information from new engine-airframe model

Figure 3.2 shows the GWP(100) and PGTP(100) for CO_2 emissions using the original LEEA methodology and the new methodology developed by JETCLIM and described in Part B of this final report (Poll, 2009). For the new methodology, the fuel use depends on the configuration of the aircraft – here the aircraft has a 3000 nm range, a Mach Number of 0.85 and takes 296 Passengers, with this configuration adopted in what follows, unless otherwise stated. By contrast with the original methodology, for which fuel use decreased with height for all heights, the new methodology shows a distinct minima in both GWP(100) and PGTP(100) at around 35 kft – this is not surprising as aircraft are optimised to minimise fuel burn at the typical cruise altitude of the present day fleet.

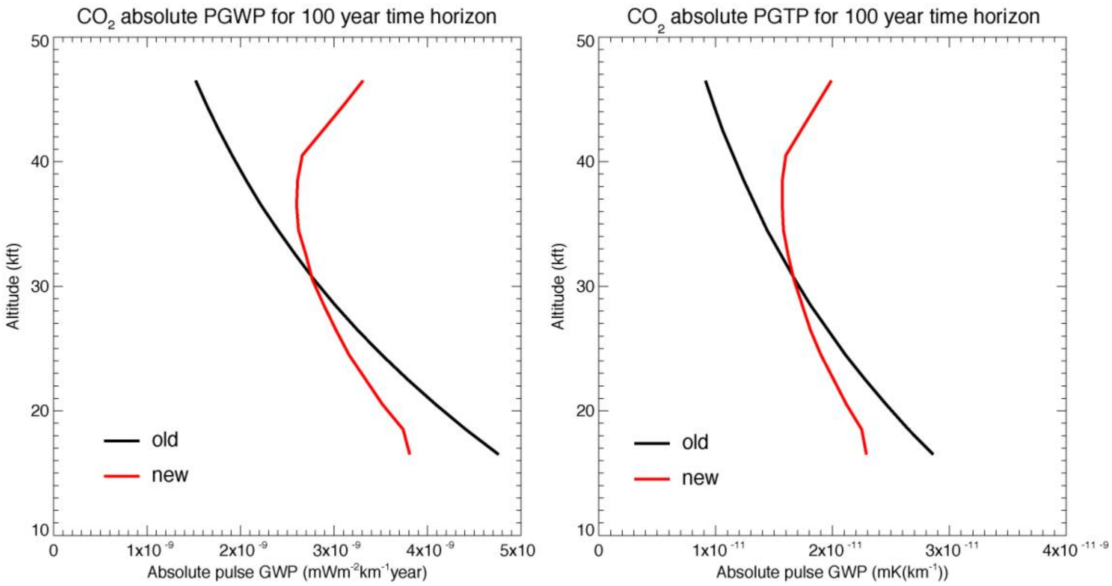

Figure 3.2: (Left) GWP(100) and (Right) PGTP(100) for CO_2 using the original LEEA method ("old") and the new methodology developed under JETCLIM. The new PGTP results assume a 3000 nm mission at a Mach Number of 0.85. *These results should be considered preliminary and are subject to change following peer review.*

2.4 Incorporation of new contrail optical depth parameterisation

Figure 3.3 shows the GWP(100) for contrails, contrasting the original LEEA methodology with the new JETCLIM parameterisation presented in Section 2. As expected from Figure 2.4, the new GWP(100) is generally lower than the old GWP(100) throughout most of the height range at which contrails can occur.

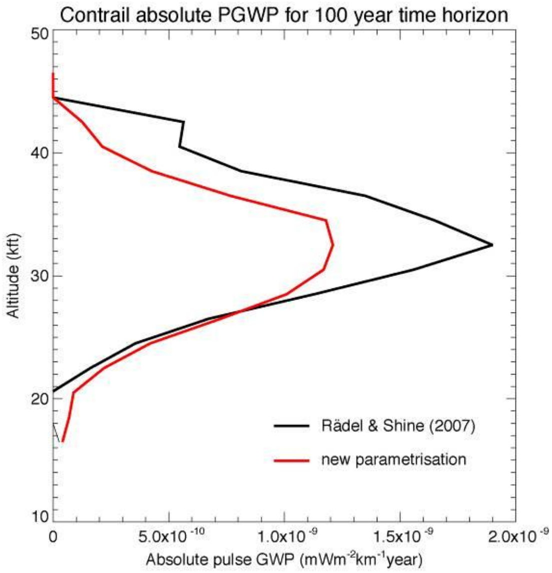

Figure 3.3: GWP(100) for contrails, comparing the original LEEA methodology and the new JETCLIM methodology, where the contrail optical pth is made dependent on temperature.

These results should be considered preliminary and are subject to change following peer review.

2.5 Effect of new JETCLIM representation on the GWP(100) and GTP(100)

Figure 3.4 shows the total GWP(100) and PGTP(100) and its components, incorporating the new JETCLIM fuel-use representation (see Part B of the final report (Poll 2009)) and contrail parameterisation. It should be contrasted with Figure 3.1, which showed the same components using the LEAA methodology. For GWP(100) the main feature is the reduction in the sharpness of the peak at around 32 kft and indeed, the general reduction of the height dependence below the peak, partly due to the reduction in contrail forcing and partly because of the change in the dependence of fuel use with altitude. For the PGTP(100) the result is notable in that it has, as expected from Section 3.3 and Figure 3.2, led to a broad minimum between 35 and 40kft where none existed before.

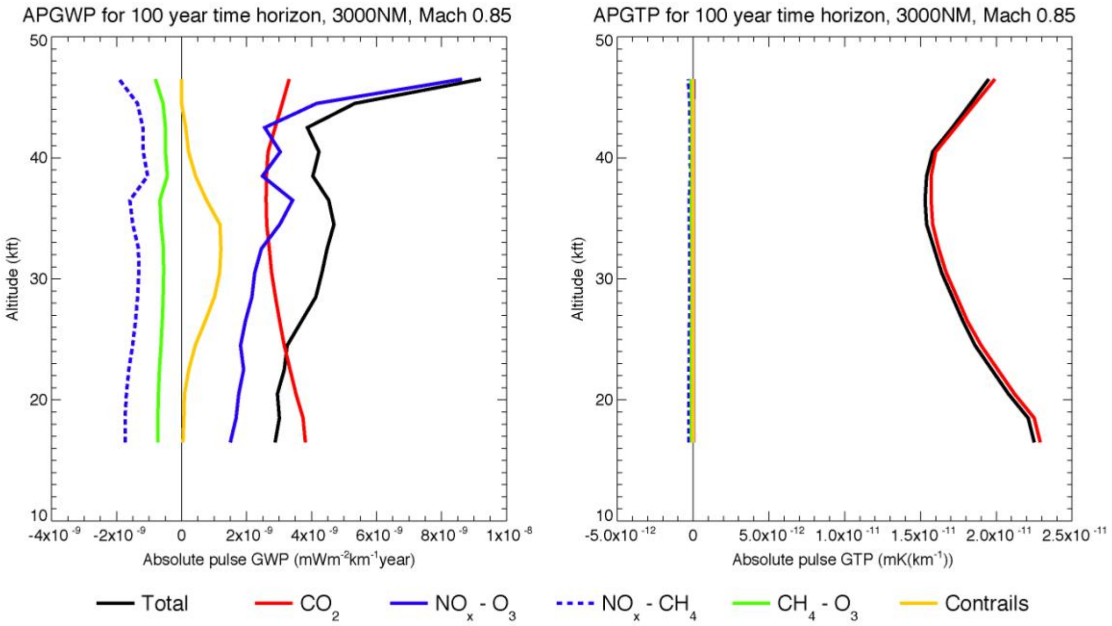

Figure 3.4: (Left) GWP (100) and (Right) PGTP (100) incorporating the new JETCLIM methodologies for fuel burn and contrails, for each as a function of cruise altitude for a 3000 nm mission and Mach number of 0.85. The coloured curves show the individual contributions of the emissions, the black line shows the total effect. ***These results should be considered preliminary and are subject to change following peer review.***

Strikingly, using these metrics alone, the implication of the two frames is quite different – for the GWP(100), despite the reduction in the size of the peak, there is still a maximum at 35kft. By contrast, the PGTP(100) shows a *minimum* at the broadly the same altitude – this emphasises the need for discerning decisions when the metric (and the associated time horizon) is chosen.

2.6 Dependence of PGTP on time horizon for different mission lengths

Figure 3.5 shows how the PGTP changes for four chosen time horizons (10, 20, 50 and 100 years) for three mission lengths (1000, 3000 and 5000 nm). It illustrates that the role of the short-lived aircraft emissions is large for the shorter time horizons (10 and 20 years) with a local maximum at 35 kft which is particularly marked for the 10 year case By contrast, at 50 and 100 years, the effect of CO_2 is dominant and there is a local *minimum* at 35kft. The figure shows that if the aim was to limit warming at say 50 years in the future, then at this stage, reducing CO_2 emissions would be the priority, but as the time when the limit is specified is approached, reducing emissions of the shorter-lived species would grow in priority.

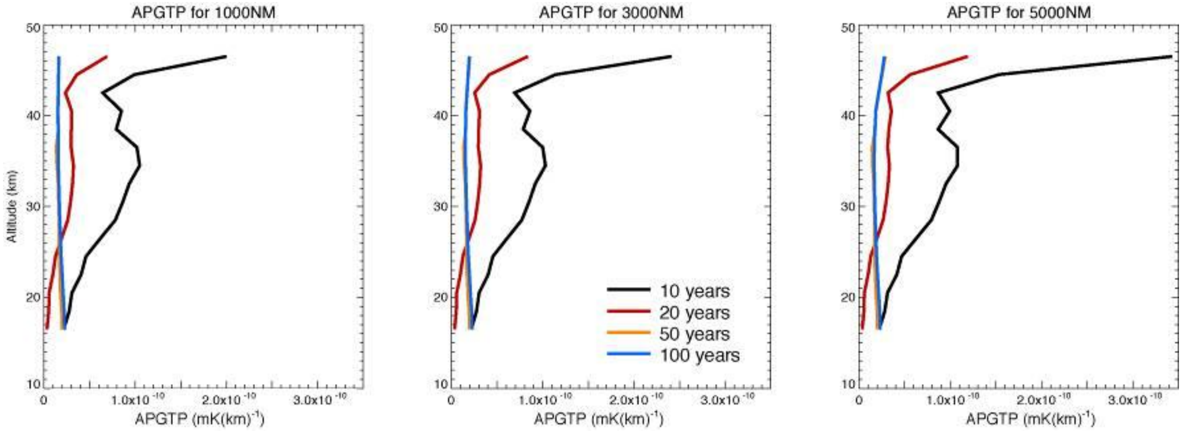

Figure 3.5: PGTP for 4 different time horizons (see legend in middle frame) for three mission lengths (1000 nm (left), 3000 nm (centre), 5000 nm (right). The 50 year curve is almost the same as the 100 year curve and hence is barely visible.
These results should be considered preliminary and are subject to change following peer review.

2.7 Dependence of PGTP on climate sensitivity

As discussed in Section 3.1, the application of the PGTP requires specification of a climate sensitivity parameter; at the present level of understanding of the climate system, there is significant uncertainty in this parameter. Figure 3.6 illustrates the way the total PGTP(50) varies as the climate sensitivity parameter is altered – on the whole, as expected, the variation in the parameter has an impact on the absolute size of the PGTP, the height variation is more modestly affected, except at higher levels.

The reason for this change in height dependence at high levels is quite complex. The change in climate sensitivity parameter not only changes the absolute value of the climate change, but also alters the time constant of the climate system. A higher climate sensitivity parameter leads to a longer time constant, which means that the short-lived forcings have a more persistent effect – at high levels there is a tight balance between the positive NO_x-ozone forcing and the negative ozone-induced ozone forcing. The change in time constant is sufficient to change the balance between the temperature responses of these forcings significantly.

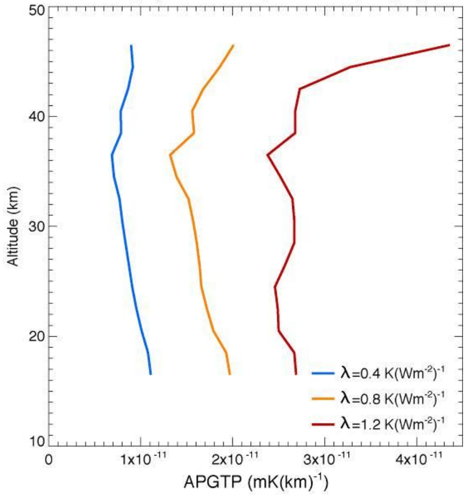

Figure 3.6 The total PGTP(50) for three different values of the climate sensitivity parameter (λ) for 3000 nm and Mach Number 0.85.
These results should be considered preliminary and are subject to change following peer review.

2.8 Dependence on contrail multiplier

A significant uncertainty in the climate impact of aviation is the role of aviation-induced cirrus. Given that uncertainty it is only appropriate, indeed possible, to crudely account for its effect here and a simple approach is adopted whereby the contrail forcing is multiplied by a single value. The standard calculations above assume the "contrail multiplier" is 5, but Figure 3.7 shows or 3 multipliers, 1, 5 and 10, all of which are possible given current uncertainties. The influence of the uncertainty is particularly acute for the AGWP(100) which retains a stronger memory of the effect of the short-lived contrail forcing – as can be seen, for the larger value of contrail multiplier, a distinct peak in the climate effect develops at around 35 kft.

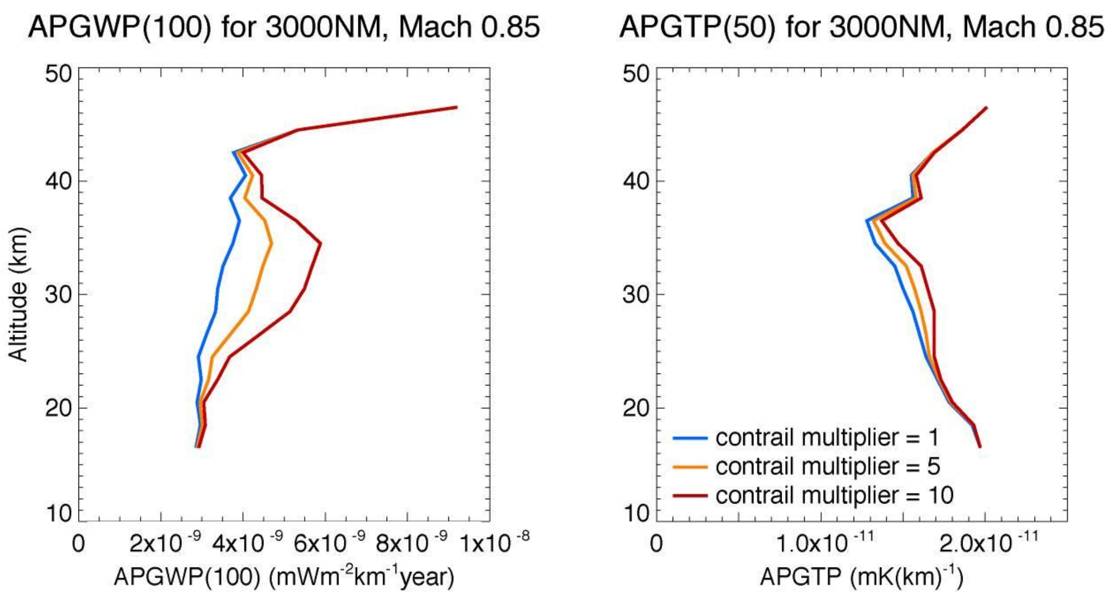

Figure 3.7: (Left) Total AGWP(100) and (right) total AGTP(50) for 3 values of contrail multiplier, for a 3000 nm and Mach Number = 0.85. ***These results should be considered preliminary and are subject to change following peer review.***

3.0 Knowledge transfer activities and final project workshop

The principal knowledge transfer activity associated with JETCLIM was the final project workshop held at the Royal Society on 29 January 2009, in which synopsis of the results discussed above were presented. This was followed by a discussion session.

The attendees at the workshop asked a variety of questions. These included:

1. The applicability of the different metrics, where it was stated that, in the context of a target-based climate policy, that the GTP(50) might be seen as appropriate;
2. the relevance of this work to the United Nations Framework Convention on Climate Change's meeting in Copenhagen in late

2009 – it was pointed out that this work would be too late to influence the outcomes there, as it would require some kind of international assessment first, although it was pointed out the IPCC was holding a special meeting on the subject of metrics in Oslo in March 2009, at which Shine would be a keynote speaker;
3. the possibility of taking existing aircraft and making them fly high or lower, to lessen their climate impact – it was pointed out that this would not be effective, as the existing fleet is optimized to fly at current cruise altitudes and there would be a severe fuel penalty if they flew away from this optimum – this was a useful point as it clarified that the work presented in the above sections was considering aircraft/engine configurations that have been optimized to fly at the particular altitudes. In response to other questions, it was emphasized that the current fleet's operation (e.g. cruise speed, engine choice) was not always optimised to reduce their climate effect. Finally, it was emphasized that the results presented in JETCLIM were for global and annual averages, and that seasonal and regional variations in the effect of aviation emissions were expected. If funding became available, it was hoped that these could be subject of future studies.

Other KT activities carried out under JETCLIM included:

- A talk to an environment workshop of the Airport Operators Association, Heathrow 25 June 2007
- A "stall" at the OMEGA Parliamentary Reception at the Houses of Parliament in May 2008
- A lecture at the OMEGA Short Course on Aviation Sustainability, Cranfield University, 17 June 2008
- A presentation at the OMEGA non-CO_2 impacts of aviation workshop at the Royal Society, 30 September 2008
- A presentation to a Greener by Design meeting at the Royal Aeronautical Society, 7 October 2008

4.0 Conclusions

JETCLIM has achieved its aims of improving understanding of the climate impact of variations in the cruise altitude of aircraft. The results must be judged against a backdrop of the existing uncertainties in two key aspects of the problem. One aspect is the fundamental uncertainty in many of the atmospheric processes of relevance to the aviation-climate question, which limits our ability to confidently model the climate impact. The second is the difficulty in defining a metric by which the climate effect of different emissions by aircraft can be placed on a common scale; there are many value-laden decisions that need to be taken concerning the choice of metric and choices of parameters within a given metric.

As has been clearly shown in Section 3, these choices have a substantial impact on the perception of the importance of the short-lived impacts of aviation (notably due to NO_x emissions, contrails and aviation induced cirrus) compared to the long-lived impact which comes from the persistence of CO_2 in the atmosphere following an emission from an aircraft. These in turn have a substantial impact on the perception of the climate impact of changes in aircraft cruise altitude. However, once these value-laden choices have been made, the JETCLIM results can give guidance on the climate impact of changing flight altitude, within the constraints of current understanding of atmospheric processes.

It is likely that the results of the work presented here will be subject to significant revision as this understanding improves, but the framework may nevertheless provide useful guidance to stakeholders in the debate on the climate, and wider environmental, impact of aviation.

5.0 References

Bakan, S., Betancor, M., Gayler, V., and Grassl, H. (1994): Contrail frequency over Europe from NOAA-satellite images. *Ann. Geophys.*, 12, 962-968.

Berntsen, T. K., Fuglestvedt, J. S., Joshi, M. M., Shine, K. P., Stuber, N., Ponater, M., Sausen, R., Hauglustaine, D. A., and Li, L. (2005): Climate response to regional emissions of ozone precursors: sensitivities and warming potentials. *Tellus*, 57B, 283-304.

Forster, P. M. D., Shine, K. P., and Stuber, N. (2006): It is premature to include non-CO_2 effects of aviation in emission trading schemes. *Atmospheric Environment*, 40, 1117-1121.

Forster, P. M. D., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Van Dorland, R. (2007a): Changes in Atmospheric Constituents and in Radiative forcing. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate change*, edited by S. Solomon, *et al.*, Cambridge University Press, Cambridge.

Forster, P. M. D., Shine, K. P., and Stuber, N. (2007b): It is premature to include non-CO2 effects of aviation in emission trading schemes (Vol. 40, pg 1117, 2006). *Atmospheric Environment*, 41, 3941-3941.

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

IPCC (1999), *Aviation and the Global Atmosphere. Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.

Köhler, M. O., Rädel, G, Dessens, O., Shine, K. P., Rogers, H. L., Wild, O., and Pyle, J. A. (2008): Impact of perturbations to nitrogen oxide emissions from global aviation. *J. Geophysical Research*, 113, D11305.

Marquart, S., Ponater, M., Mager, F., and Sausen, R. (2003): Future development of contrail cover, optical depth and radiative forcing: impacts of increasing air traffic and climate change. *J. Climate*, 16, 2890-2904.

Meyer, B., Mannstein, H., Meerkötter, R., Schumman, U., and Wendling, P. (2002): Regional radiative forcing by line-shaped contrails derived from satellite data. *J. Geophysical Research*, 107, D10, doi:10.1029/2001JD000426.

Meyer, R., Buell, R., Leiter, C., Mannstein, H., Pechtl, S., Oki, T., and Wendling, P. (2007): Contrail observations over southern and eastern Asia in NOAA/AVHRR data and comparisons to contrail simulations in a GCM. *Int. J. Remote Sensing*, 28, 2049-2069.

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

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

Poll, D.I.A. (2009) Project JETCLIM Final Report – Part B. Combing models of jet engine exhaust and climate impact to quantify trade-offs of changes in engine design and operation. www.omega.mmu.ac.uk

Ponater, M., Marquart, S., and Sausen, R. (2002): Contrails in a comprehensive global climate model: Parameterization and radiative forcing results. *J. Geophysical Research*, 107, D13, doi:10.1029/2002JD000429.

Rädel, G. and Shine, K. P. (2007): Evaluation of the use of radiosonde humidity data to predict the occurrence of persistent contrails. *Q. J. R. Meteorol. Soc.*, 133, 1413-1423.

Rädel, G. and Shine, K. P. (2008): Radiative forcing by persistent contrails and its dependence on cruise altitudes. *J. Geophysical Research*, 113, D07105, doi:10.1029/2007JD009117.

Reddy, M. S., and Boucher, O. (2007): Climate impact of black carbon emitted from energy consumption in the world's regions. *Geophy. Res. Lett.*, 34.

Sausen, R., Gierens, K., Ponater, M., and Schumann, U. (1998): A diagnostic study of the global distribution of contrails, Part I: Present day climate. *Theor. Appl, Climatol.*, 63, 1-9.

Schumann, U. (2002): Contrail Cirrus. In *Cirrus*, edited by Lynch, D. K., Sassen, K., Starr, D, O'C, Stephens, G., 2002, Oxford University Press.

Shine, K. P., Berntsen, T. K., Fuglestvedt, J. S., Bieltvedt Skeie, R., and Stuber, N. (2007): Comparing the climate effect of emissions of short- and long-lived climate agents. *Philosophical Transactions of the Royal Society A*, 365, 1903-1914.

Shine, K. P., Fuglestvedt, J. S., Hailemariam, K., and Stuber, N. (2005): Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change*, 68, 281-302.