On the potential of the cryoplane technology to reduce aircraft climate impact

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ABSTRACT: The quantitative potential of a switch to cryoplanes to reduce aircraft climate impact is investigated. Basic assumptions are the expected increase of air traffic between 1990 and 2050 and a smooth technology transition between 2015 and 2050. The study covers the effects of reduced CO_2 emissions, reduced NO_x emissions, and a change in contrail radiative impact to be expected from increased coverage and decreased optical depth in the cryoplane case. We find a typical value of about 20% reduction in aircraft induced radiative forcing on the 2050 horizon, if cryoplanes were introduced. Best estimates range between 16% and 29%, depending on the speed of the technology transition. Due to inherent scientific uncertainties this range widens to between 14% and 40%. Some further sources of uncertainty like cirrus cloud changes or possible CO_2 emissions from the liquid hydrogen production process could not be included in the current estimate.

1 INTRODUCTION

One technological option to reduce the climate impact of air traffic is a switch to alternative fuels like liquid hydrogen (LH_2). The main advantage of this so-called cryoplane technology over conventional kerosene engines is the elimination of, both, CO_2 and particle emissions, while a lower NO_x emission index is also expected due to the extended possibilities to employ lean burning (e.g., the "micromix combustion" described by Dahl and Suttrop, 1998). In contrast, the net effect of enhanced water vapour emissions of LH_2 engines on the stratospheric water vapour content has been estimated to be of little importance, as long as flight altitudes are not lifted upward (IPCC, 1999). A first attempt to assess net climate impact gain due to cryoplane operation (Marquart et al., 2001) suggested that the higher formation frequency of contrails (also resulting from more water vapour in the exhaust gas) may strongly counteract the various advantages at least on the shorter time range, as the effect of vanishing CO_2 emissions is mainly felt on longer time horizons. Here, we report on recent results yielded within the EU-project *CRYOPLANE*, which have extended the respective assessment basis in several respects: First, a number of more realistic transition scenarios has been developed. Second, the treatment of the contrail impact has been refined beyond the work of Marquart et al. (2001): Potentially different optical properties of contrails from cryoplanes due to the absence of particles in the exhaust have been included.

2 TOOLS AND METHODS

Several models were employed to quantify key parameters of aircraft climate impact on the microphysical up to the global scale. Contrail microphysics was simulated in the framework of the MESOSCOP model (e.g., Ström and Gierens, 2002). The global distribution of contrails including their radiative forcing was determined with the ECHAM4.L39(DLR) GCM using a parameterisation scheme of Ponater et al. (2002) and Marquart and Mayer (2002). The climate impact of atmospheric ozone changes caused by aircraft NO_x emissions was treated as in Grewe et al. (1999), some new

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simulations for a crosscheck of the IPCC (1999) CTM results were run with the more recent coupled chemistry/climate model E39/C (Grewe et al., 2002). The evaluation of the transient transition scenarios to the cryoplane technology was done by applying of the global mean linear response model of Sausen and Schumann (2000).

3 CRYOPLANE CONTRAILS

3.1 *Simulation of microphysical parameters*

Two pairs of case studies for contrails behind either kerosene or hydrogen fuelled aircraft under the same ambient conditions have been described in detail by Ström and Gierens (2002). The number of these simulations was extended to scan the parameter space of possible ambient conditions (Fig. 1, left) in order to identify characteristic differences in ice water path, ice crystal concentration, optical depths etc. for a global assessment. The key parameter is the ice crystal size (effective radius r_{eff}). In MESOSCOP, it is calculated as a spatial distribution from the respective distributions simulated for ice mass and ice crystal number concentration. This information must be translated to the bulk formulation in the global model, which only knows a mean effective radius for the grid box averaged contrails as a whole (Roeckner, 1995). As discussed in Ström and Gierens (2002), absolute values of r_{eff} and of the optical depth τ (taken as means over a 30 minute simulation) are sensitive to many uncertainties arising from background aerosols, ice crystal shape, presence of wind shear etc., but also to some ambiguity in determining the mean r_{eff} (mass weighted or crystal density weighted). We decided to characterise the different contrail optical properties by using the r_{eff} ratio (Fig. 1, right) between the conventional and the cryoplane case, which appears to be quite a robust quantity.

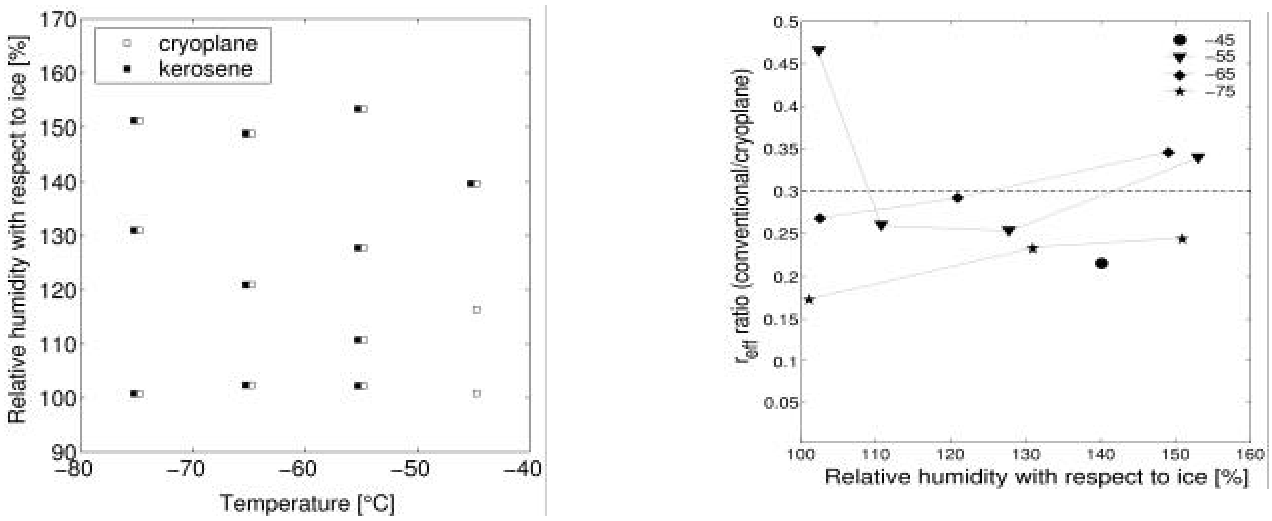

Figure 1. Left: Overview on the ensemble of contrail simulations performed with the MESOSCOP microphysical model for various ambient temperature and supersaturation conditions (in two cases the thermodynamic theory does only allow contrails behind the cryoplane). Right: Ratio of the mean effective ice particle radii (conventional vs. cryoplane case) for the various pairs of MESOSCOP simulations.

Rather than trying to define an analytical function of this ratio dependent on temperature and ice supersaturation we assumed r_{eff} in conventional contrails to be smaller by a factor of 0.3 than in cryoplane contrails. This implies that the optical depth of cryoplane contrails is smaller by a similar amount, as the contrail ice water content is mainly determined by the supersaturation in the ambient air and, thus, almost independent from the engine technology.

3.2 *Simulation of global impact*

In order to determine the global radiative forcing of contrails we have evaluated future scenarios for 2015 and 2050, assuming changes in, both, air traffic density and propulsion efficiency as described in Marquart et al. (2003). Potential changes in the background climate were not included. As the contrail parameterisation in the ECHAM4 global climate model is based on the thermodynamic theory, the changes of contrail coverage due to increasing propulsion efficiency (from 2015 to 2050), or a higher H_2O emission index (of LH_2 engines compared to kerosene engines) are implicitly accounted for (Marquart et al., 2001; Ponater et al., 2002). The difference in contrail optical properties was introduced by prescribing larger particles in the cryoplane case as explained in the previous subsection.[6] The reference values of global mean contrail radiative forcing in a conventional aircraft scenario are 9.8 mW/m^2 and 19.5 mW/m^2 for 2015 and 2050, respectively. Note that these values are substantially smaller than those given by IPCC (1999) from methodical reasons discussed in detail by Ponater et al. (2002) and Marquart et al. (2003). The general reduction of estimated contrail climate impact compared to IPCC (1999) also implies an *a priori* reduction of the importance of respective changes due to a potential transition to the cryoplane technology.

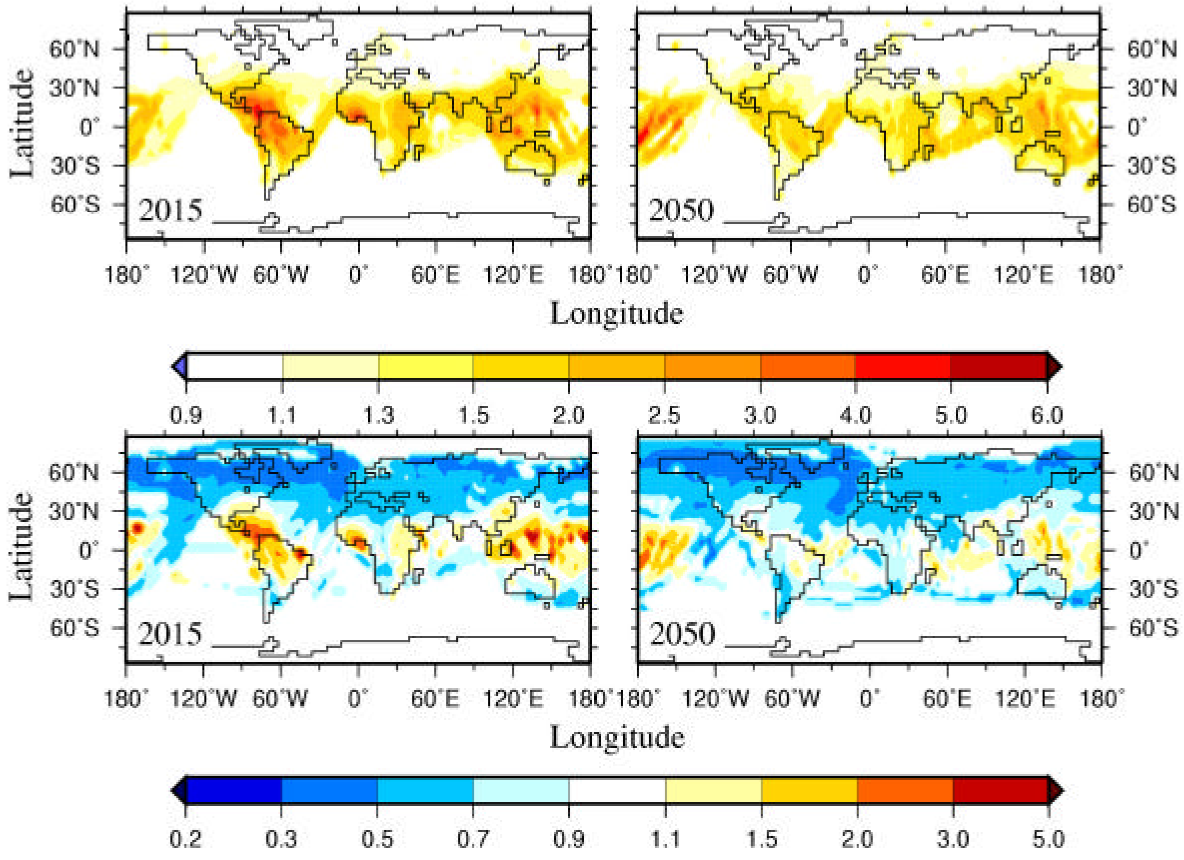

Figure 2. Ratio of the results yielded in a conventional aircraft scenario and a equivalent cryoplane scenario for the annually averaged coverage of all contrails (upper panels) and the associated net radiative forcing (lower panels), respectively. Two examples based on a 2015 (left) and a 2050 (right) aircraft scenario are displayed. Blue (yellow/red) colour indicates a smaller (larger) value for the cryoplane case.

Fig. 2 indicates the maximum impact of the technology transition for 2015 and 2050, relating pure cryoplane to pure conventional air traffic for each time slice. The upper panel shows the ratio of contrail coverage between the cryoplane and the conventional case, the lower panel the respective ratio of contrail radiative forcing. Contrail coverage is enhanced everywhere in the cryoplane

[6] Actually, this means an increase from about 12 to 13 µm for normal contrails (Ponater et al., 2002) to 40 to 44 µm for cryoplane contrails.

scenarios as thermodynamic contrail formation is possible under less restrictive ambient conditions. However, in most regions of the world the effect of reduced optical depth outweighs the effect of increasing coverage. This holds, particularly, in the extratropics where air traffic density is highest. The net effect is a reduction of contrail global radiative forcing by about 18% in 2015 and by about 28% in 2050 (from 9.8 mW/m^2 to 8.0 mW/m^2 and from 19.5 mW/m^2 to 13.9 mW/m^2, respectively). To illustrate the importance of changing optical properties we note that the radiative forcing in 2015 would increase from 9.8 mW/m^2 to 16.5 mW/m^2, if the lower optical depth of cryoplane were not accounted for.

4 TRANSITION SCENARIOS

4.1 *Technology transition*

Several technological transition scenarios were developed within the *CRYOPLANE* project, three of which (designated as Cryo1, Cryo2, and Cryo3) have been evaluated for the present study and are described here. They assume introduction of the first cryoplanes between 2015 and 2020, followed by continuous transition during the period until 2050 (instead of the artificial instantaneous switch assumed in Marquart et al., 2001). Cryo1 represents a smoothed, stepwise approach with the EU taking the lead, followed 5 years later by a transition start in North America, and another five years later in Latin America, Asia, and the Middle East. In each case cryoplane introduction starts with the smallest aircraft, with long-range aircraft following about ten years after. Cryo2 assumes the fastest transition, starting a smooth world-wide transition of small and medium-sized aircraft in 2015, and of large aircraft in 2025. Transition of the whole fleet is complete in 2050. Cryo3 starts a world-wide transition later (2020) than Cryo2 but lets proceed it faster towards the end of the period.

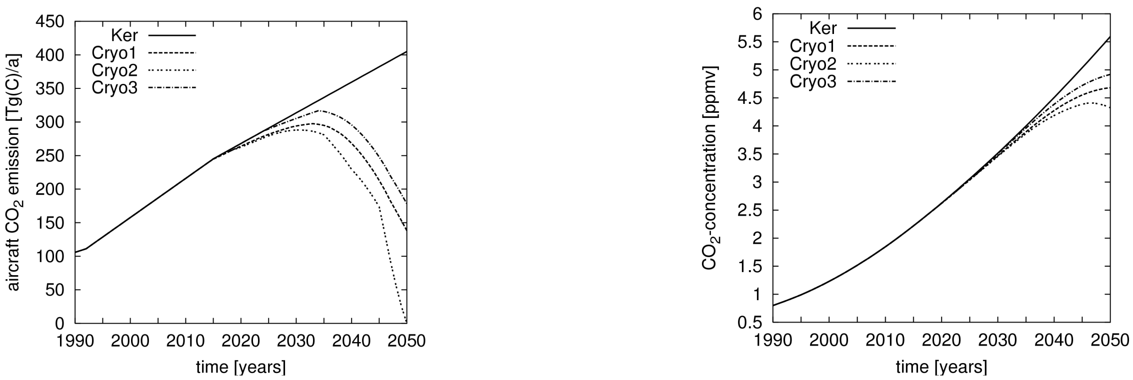

Figure 3. Temporal evolution of aircraft induced CO_2 emissions (left) and atmospheric CO_2 concentration increase (right) for a purely kerosene supported aircraft inventory (Ker) and for three transition scenarios to cryoplane technology (Cryo1/2/3, see text) from 1990 to 2015. The numbers indicate global mean values.

All emission scenarios are based on approved air traffic increase expectations (IPCC, 1999). The relative kerosene and LH_2 consumption has been calculated for every fifth year, thus CO_2, H_2O, and NO_x emissions can be derived, accordingly. As an example, Fig. 3 displays the time development of aircraft global mean CO_2 emissions for a purely kerosene supported scenario (Ker) and for the transition assumptions just described. There is no difference between the scenarios before 2015. The related CO_2 concentration change is derived from the linear response model of Sausen and Schumann (2000): Due to the long lifetime of CO_2, its concentration continues to rise for most scenarios until 2050 as long as CO_2 emission rates of the remaining conventional aircraft dominate the CO_2 removal rates from the atmosphere.

4.2 *Climate impact change*

The climate impact associated with the various scenarios is quantified in terms of the global mean radiative forcing in 2050 (Fig. 4). We also adopt the usual method of taking radiative forcing as a metric to compare individual components to the net effect (e.g., IPCC, 1999). The aircraft CO_2 forcing and its variability among the scenarios is directly related to the concentration changes shown in Fig. 3, right. The CO_2 contribution to the radiative impact gain drops from 73 mW/m^2 in Ker to 56 mW/m^2 in Cryo2, the fastest transition scenario. While this component can be regarded to be quantified with a good reliability, the other ones are more uncertain. The ozone contributions to the radiative forcing have been scaled linearly on the basis of global mean aircraft NO_x emissions, just as described in Marquart et al. (2001). Our best estimate with respect to the ozone effect is based on the availability of low-NO_x technology for conventional as well as for cryoplane engines. This results in a decrease of ozone radiative forcing in 2050 from 36 mW/m^2 (Ker) to 9 mW/m^2 (Cryo2). However, part of this effect is compensated by the impact of atmospheric NO_x increase on methane lifetime. Thus, in accordance with current estimates (IPCC, 1999; Isaksen et al., 2001), we reduce the ozone related values by 75%, which leaves a net impact of NO_x between about 9 mW/m^2 (Ker) and about 2 mW/m^2 (Cryo2). For the contribution of contrails we rely on the key numbers described in subsection 3.2. This implies a radiative forcing reduction at 2050 time horizon from 19.5 mW/m^2 (Ker) through 16 mW/m^2 (Cryo1) down to about 14 mW/m^2 (Cryo2).

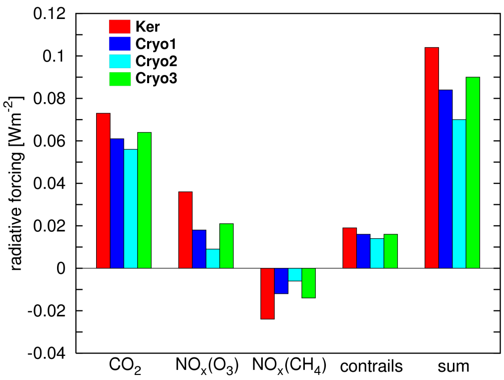

Figure 4. Radiative forcing best estimates (in W/m^2) of CO_2, NO_x (through either O_3 or CH_4 concentration changes), and contrails at year 2050 for a conventional aircraft increase scenario (Ker) and three transition scenarios to cryoplanes (Cryo 1/2/3). The columns represent global mean values. The rightmost panel shows the sum of all displayed components, not including further contributions from soot and sulfur aerosols, stratospheric water vapour, and cloudiness beyond line-shaped contrails.

The sum of effects suggests a best estimate of the net climate impact reduction at 2050 from about 100 mW/m^2 for kerosene supported air traffic throughout the whole period to between 85 mW/m^2 and 72 mW/m^2 for the various cryoplane transition scenarios.

We recall that the radiative forcing of contrails and aircraft NO_x emissions is known only with considerable caveats. The respective general uncertainty discussions in IPCC (1999) continue to be valid. However, we have chosen key values for the radiative impact change due to cryoplanes that are rather conservative (i.e., on the low side), for example by including low-NO_x technology for conventional aircraft, and by employing the lower estimates for contrail climate impact by Marquart et al. (2003) instead of the respective values from Minnis et al. (1999) adopted by IPCC (1999) that yield a five times larger best estimate. This approach reduces the possibility that we overestimate the environmental gain by a cryoplane transition. However, if the LH_2 fuel could not be produced totally from renewable energy sources (but would cause extra CO_2 emissions in the production process), the climate impact gain would be diminished, of course. These, as other contributions, may easily be fed into the linear response model as soon as reliable key numbers become available.

5 DISCUSSION AND OUTLOOK

According to our best estimate a relative reduction of aircraft induced radiative forcing at 2050 by between 16% and 29% (depending on the speed of transition) could be achieved if cryoplanes were introduced. The uncertainty range widens to between 14% and 40%, if several inherent scientific uncertainties with respect to individual processes and effects are taken into account. Note also that these values depend on the year considered, due to the gradual increase of the CO2 contribution (Fig. 3, right). Beyond the 2050 time horizon the environmental gain in the cryoplane scenarios would obviously grow, as the continuing CO_2 emissions of the kerosene supported fleet would further increase the effect of accumulated CO_2 concentration in the atmosphere.

We have not included in our best estimate most recent results (Morris et al., 2003; Gauss et al., 2003) suggesting that accumulation of aircraft water vapour emissions in the stratosphere may be more important than assumed by IPCC (1999) and by Marquart et al. (2001). However, we do not expect that it would make a qualitative change to our overall assessment. A potential uncertainty source of greater importance is contrail cirrus, which is now suspected to cause a larger climate impact than line-shaped contrails (e.g., Mannstein, this volume). There is no sufficient knowledge at this stage to include this effect in a quantitative assessment, but respective research is proceeding rapidly (see several contributions in this volume). More knowledge is also warranted with respect to the potential of producing large amounts of LH_2 from renewable energy sources. Finally, we note the necessity to have at least some measurements from observed cryoplane contrails in order to support the results of our contrail microphysics simulations.

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Impact of Cruise Altitude on Contrails

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Keywords: contrails, radiative forcing, cruise altitude, aircraft

ABSTRACT: The ECHAM general circulation model and a recently developed contrail parameterisation were applied to a set of three-dimensional aircraft inventories with shifted cruise altitudes in a parametric study. Contrail coverage and radiative forcing, including regional and seasonal differences, for changed cruise altitudes of 610 m (2000 feet) increments were compared with a ‘base case’ scenario. The global annual mean contrail coverage decreased in an approximately linear manner to a maximum change of -45% for a decrease of 1830 m (6000 feet) in cruise altitudes. Our best estimate for radiative forcing by contrails is a decrease of 45% for the maximum shift in cruise altitudes. Fuel burn of the global fleet increased as a consequence of the downward shift in cruise altitudes.

1 INTRODUCTION

Actual cruise altitudes of aircraft are not optimised with respect to minimal overall environmental impact, but result mainly from fuel or flight time efficiency with the constraints imposed by aircraft aerodynamics and air traffic management. Climate impact is not considered in this process. However, this impact might be reduced by changing the flight altitude. Of particular interest is the impact of flight altitude on contrail formation.

According to the revised thermodynamic Schmidt-Appleman theory (Schumann, 1996), contrail formation depends on the overall propulsion efficiency of the aircraft, the emission index of water vapour and ambient atmospheric conditions of pressure, humidity, and temperature. Figure 1 shows the zonal mean potential contrail cover, which is a measure for the ability of the air to allow contrail formation (Sausen et al., 1998), for January and July mean conditions of the 1990s as calculated with the ECHAM4.L39(DLR) GCM (Land et al. 1999a; Land et al., 2002) extended by a parameterisation for persistent contrails (Ponater et al., 2002).

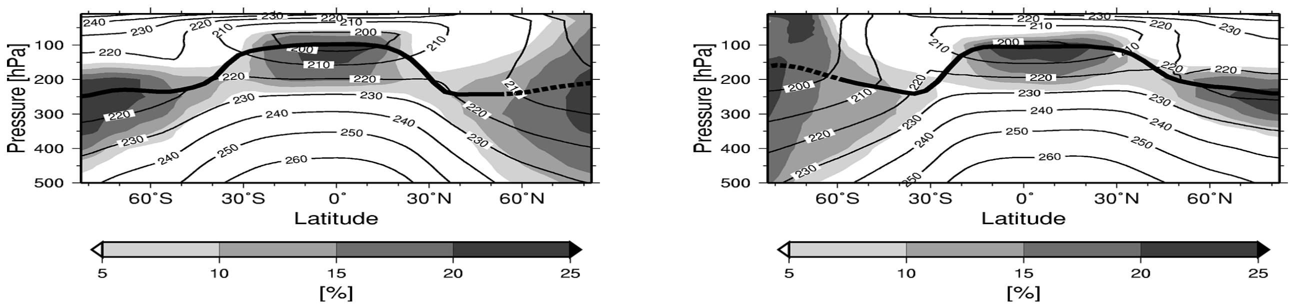

Figure 1: Five year zonal mean of potential contrail coverage (shading, in %) for January (left) and July (right) mean conditions as calculated by ECHAM4.L39(DLR). The bold line indicates the thermal tropopause, which is not well defined in the polar winter atmosphere (dotted). The isolines display the temperature [K].

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Table 1: Flown distance, fuel consumption, contrail cover, and net radiative forcing by contrails for the base case of the TRADEOFF aircraft emissions of the year 1991/1992, and relative changes arising from upward and downward shifting of the mean cruise altitude.

Case	Flown Distance	Fuel Consumption	Contrail Cover	net RF by Contrails[1]
+2kft	0%	- 0.45 %	+ 5.5 %	+ 5.3% (5,2%)
base case	$1.71\ 10^{10}$ km	111.5 Tg	0.0472	1.9 mW/m^2 (2.9 mW/m^2)
–2kft	0%	+ 2.69 %	- 12.7 %	- 15.8% (13,8 %)
–4kft	0%	+ 3.59 %	- 28.4 %	- 31.6 % (31,0 %)
–6kft	0%	+ 5.83 %	- 44.5 %	- 47.4 % (44,8 %)

[1] Values in brackets are adjusted by a 25% offset to the longwave contrail radiative forcing (Marquart and Mayer, 2002)

Areas that are cold and moist enough to allow the formation of persistent contrails mainly occur in the tropopause region. As aircraft usually cruise at altitudes between 200 and 250 hPa, they fly in regions where contrails are most likely to form especially in the extra-tropics. As a consequence, contrail coverage might be reduced by shifting cruise altitudes to higher or lower levels.

Sausen et al. (1998) studied the impact of cruise altitude on contrail coverage, by simply shifting the air traffic 1 km up and down relative to a base case. They did not consider aerodynamic constraints or the impact on fuel burn. In this study, the TRADEOFF aircraft emission inventory was used, which calculates ’real’ shifts in mean cruise altitudes, including the impact on fuel consumption (Table 1). The TRADEOFF inventory comprises also the flown distance, i.e., the flown distances per grid box. The effects on contrail coverage were calculated by shifting the mean cruise altitude down by 2000 ft (610 m), 4000 ft (1220 m) and 6000 ft (1830 m) and up by 2000 ft (610 m). Regional and seasonal effects were studied, and the relationship between changes in flight altitude and contrail coverage was investigated.

2 AIRCRAFT EMISSION SCENARIOS

The three-dimensional aircraft emission inventories, representative for the year 1991/92, have been produced on the basis of the ANCAT/EC2 movements database using a similar methodoloy to that of Gardner et al. (1998). The data are provided in a horizontal resolution of 1° x 1° and a vertical resolution of 2000 feet (610 m). The four seasons are represented by the months January, April, July, and October. The vertical distribution of air traffic for the base case was taken from a statistical analysis of ~53,000 real flights. For the downward shifts, this distribution was applied by simply recalculating emissions by the incremental changes. In the case of the upward shift, not all aircraft could perform this, so only those that could do so were shifted upwards. A summary of the inventories is given in Table 1.

3 METHOD

A contrail parameterisation scheme (Ponater et al., 2002) for the ECHAM4.L39(DLR) general circulation model was utilised. In this scheme, an online determination of contrail coverage, optical properties of the contrails and the resulting radiative forcing is possible. The contrail coverage in a reference area was calibrated using satellite observations of Bakan et al. (1994). A detailed description of this calibration method is given by Marquart et al. (2003). In contrast to the diagnostic study of Sausen et al. (1998), we use flown distance instead of fuel consumption to compute contrail coverage. This approach is likely to provide more realistic results, especially if regions with predominantly short haul flights with narrow bodies, e.g., Europe, are compared with long haul traffic regions with wide bodies and high fuel consumption per km, e.g., the north Atlantic flight corridor (Gierens et al., 1999; Marquart et al., this issue). Furthermore, the TRADEOFF aircraft inventories provide a higher vertical and horizontal resolution than the DLR inventory used by Sausen et al. (1998).

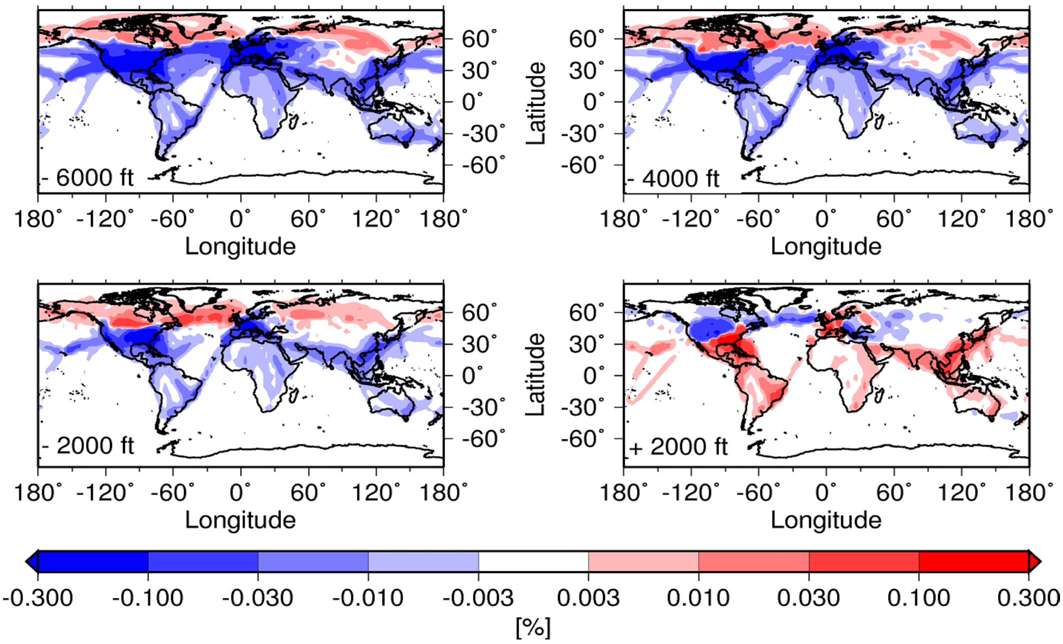

Figure 2: Absolute changes [% of the total area] of the annual mean contrail cover due to shifted flight altitudes by 6000 ft down (upper left), 4000 ft down (upper right), 2000 ft down (lower left), and 2000 ft up relative to the base case.

4 RESULTS AND DISCUSSION

4.1 *The impact of flight altitude*

Figure 2 shows the absolute changes of annual mean coverage by line-shaped contrails arising from changed cruise altitudes. The general pattern of changes in contrail coverage is similar for the three scenarios with lower cruise altitudes. In contrast to this, an almost inverted pattern appears for an up-shift of air traffic.

Downward shifting of cruise altitudes leads to a reduction of contrail coverage in the tropics and in parts of the mid-latitudes, but results in an increase of contrail coverage in the northern extra-tropics. In tropical regions the cruise altitudes of aircraft are usually located well below the tropopause (Fig. 1). If air traffic is shifted downwards it enters tropospheric regions with air that is too warm for contrail formation. Tropical contrail coverage is thus reduced with downward shifts in cruise altitudes. Figure 3 shows that nearly no contrails form in the tropics if cruise altitudes are lowered by 6000 feet.

Contrary to this, contrail coverage increases north of about 45°N, if aircraft cruise altitudes are shifted downwards. In the base case, air traffic occurs to some extent in the cold but dry stratosphere. Flying at a lower altitude in moister ambient air results in more contrails. The maximum increase in contrail coverage in the extra-tropics is associated with a downward shift of 2000 feet. In this case, cruise altitudes are shifted exactly into the region where conditions for contrail formation are optimal.

The distinct separation line between decrease and increase of contrail coverage due to downshift of air traffic mainly depends on ambient ice supersaturation and temperature. This line is shifted northwards, the more the cruise altitudes are shifted downwards. The short haul flights over the North American and European continents build an exception as they already occur in tropospheric regions and will be shifted into zones that are too warm for contrail formation when aircraft cruise at lower altitudes. However, shifting air traffic downwards results in an overall reduction of annual mean values of global contrail coverage. Almost half of all contrails disappear in the annual mean for the minus 6000 feet scenario (Table 1).

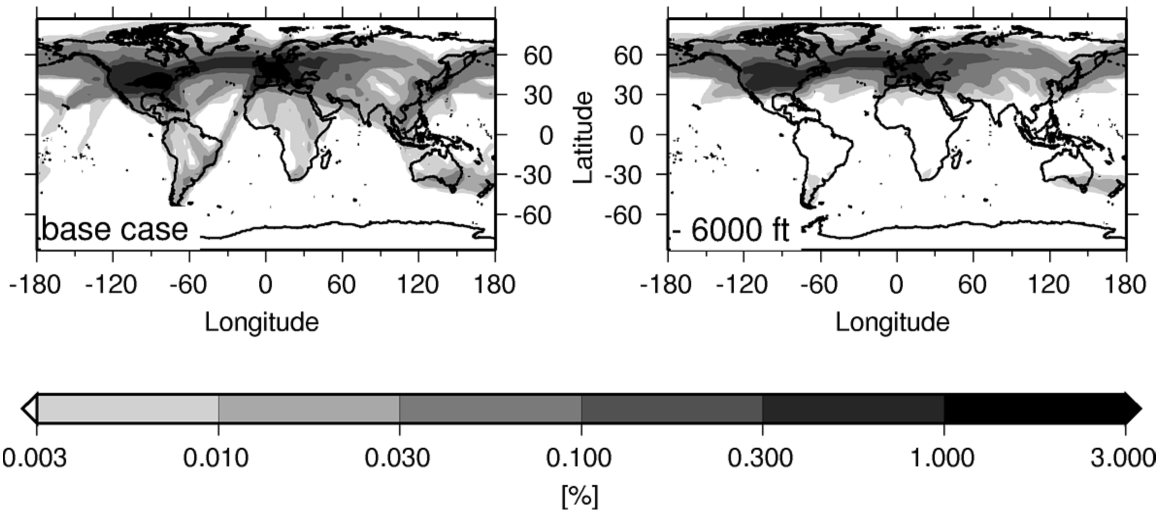

Figure 3: Geographical distribution of contrail cover for the base case aircraft emission scenario (left), and for an aircraft emission scenario with a 6000 ft lower cruise altitude.

Shifting the air traffic upward reveals an almost inverted pattern. Flying 2000 feet higher leads to an increase in contrail coverage over the tropics and parts of North America and Europe. In contrast to this, the remaining parts of the northern extra-tropics show a reduction of contrails. In the tropics air temperatures at usual cruise altitudes are mostly too warm for contrail formation. By shifting cruise altitudes upwards, air traffic enters colder regions where more contrails can be formed. Over the European and North American continents air traffic occurs to some extent in lower tropospheric regions, especially for short-range flights, so that an upwards shift of cruise altitudes does not imply shifting the air traffic into stratospheric regions where it would be too dry for contrail formation, but into colder tropospheric regions. Over Canada, the north-western parts of America, the north Atlantic flight corridor, Eastern Europe, the near Middle East and parts of Russia, cruise altitudes are high enough that shifting flight altitude up by 2000 feet has the consequence that a sufficiently large part of air traffic would enter the stratosphere, where ambient humidity is too low for contrail formation, and therefore an upwards shift of cruise altitudes results in a reduction of contrail cover.

4.2 *Seasonal variation*

As tropopause height, atmospheric temperature and humidity show large variability between summer and winter months, the impact of changes in cruise altitude on contrail coverage is highly sensitive to seasons. As an example, the geographical distribution of changes in contrail coverage due to downwards shifted air traffic by 6000 feet for January and July is shown in Figure 4.

The primary differences between January and July for a downwards shift of air traffic occur in the northern extra-tropics. In general, the separation line between increases and decreases in contrail coverage due to lower flight altitudes is shifted southwards in winter and northwards in summer. In January tropospheric regions in the extra-tropics are cold and moist enough that an increase in contrail coverage due to lower cruise altitudes results, whereas in July, the higher upper tropospheric temperatures in the extra-tropics prevent further contrail formation if air traffic is shifted down. This results in a relative decrease in contrail cover in July by about 50% over the North American and the European continents, and the north Atlantic flight corridor compared with the base case. A similar but less pronounced pattern is also found for a smaller downwards shift of air traffic by 2000 or 4000 feet (not shown).

Seasonal differences are found also for the plus 2000 feet scenario (not shown). In July an upwards shift of air traffic results in an overall increase in contrail cover except for very small regions over Canada and the Northeast Pacific and the Northeast of Europe. In several regions (e.g. Central Europe, North America, and South-East-Asia) this leads to a relative increase in contrail cover of more than 50% compared to the base case. In January however, increases in contrail cover are only found in the tropics, whereas in the extra-tropics contrail cover is reduced. The only exception is Central Europe, where flight altitude is so low that an up-shift still leads to an increase in contrail cover.

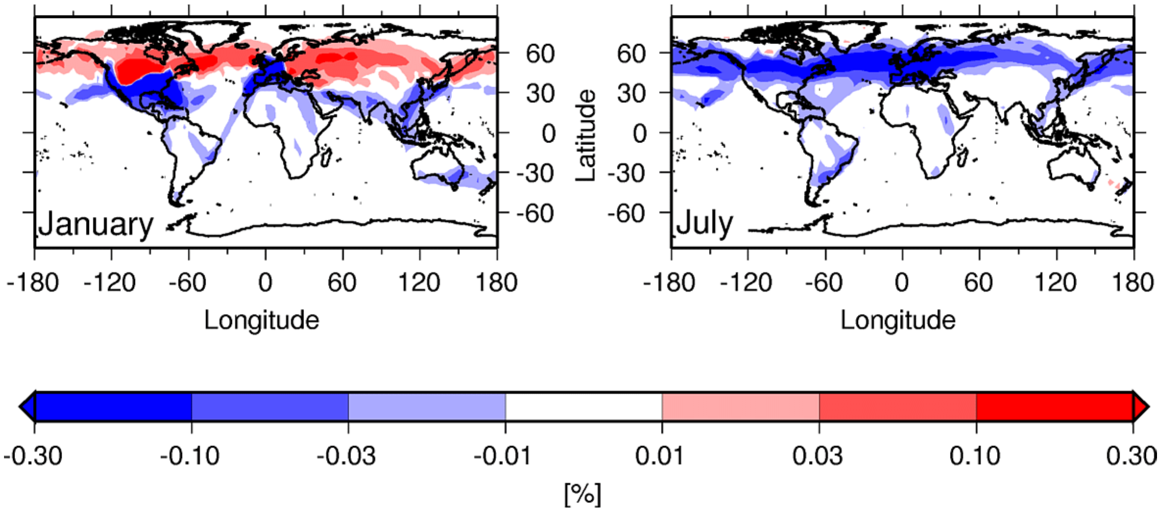

Figure 4: Geographical distribution of absolute changes in contrail cover due to 6000 feet lowered flight altitudes for January (left) and July (right).

Although the seasonal variation in global air traffic is almost negligible, global mean values of contrail coverage for January and July show very large seasonal differences for the investigated scenarios (Figure 5, left). They are even of opposite sign for an upwards shift of air traffic by 2000 feet. This seasonal differences in global contrail coverage mainly result from seasonal changes in meteorological conditions.

As the optical depth of contrails depends on ambient temperatures of contrail formation, values of optical depth are higher for lower flight altitudes and for warmer seasons (Ponater et al., 2002). However altitude dependence and seasonal variation in optical depth is very small compared to changes in total contrail coverage for different seasons and flight altitudes. Therefore seasonal differences in radiative forcing by contrails (Figure 5, right) are dominated by changes in total contrail coverage, as the curves for changes in contrail coverage and radiative forcing by contrails look qualitatively quite similar. Annual mean values for radiative forcing can be found in Table 1.

5 CONCLUSIONS

This parametric study allows a first estimation of the potential for mitigation of global environmental impacts of air traffic with respect to contrails and contrail radiative forcing by changing cruise altitudes. Strong seasonal sensitivity and considerable regional differences in contrail cover changes for the investigated emission scenarios were found. For global and annual mean values, the strongest reduction in contrail coverage were achieved by shifting air traffic down, whereas an upwards shift in air traffic resulted in a very small increase in contrail coverage. Our study shows a large potential for reducing the climate impact of aviation by including the constraint of minimal contrail formation in an air traffic management system. Evidently, this potential mitigation strategy could be optimised by considering changes in cruise altitude by latitude and season, as well as short-term changes in ambient parameters. Further work is necessary to investigate this. Moreover, quantitative estimates of aircraft impacts other than contrails need to be made before such mitigation strategies are suggested as practical options.

We note that the ECHAM4.L39(DLR) model suffers from a temperature error in the extratropical tropopause region ('cold bias'), which is expected to influence contrail formation (Marquart et al., 2003). Sensitivity experiments for varying flight altitudes were also run with a model version in which the cold bias is artificially reduced to half its value in the original model (Michael Ponater, pers. communication). Compared to the original model version contrail coverage and radiative forcing by contrails change only to a small extent in magnitude and not in sign. Therefore the main conclusions of this article appear to be largely insensitive to this temperature error.

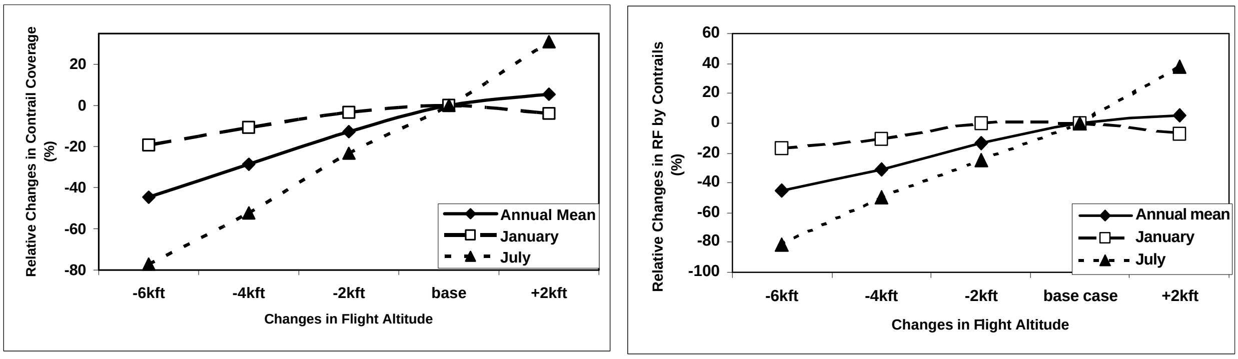

Figure 5: Relative changes in global mean contrail cover (left) and radiative forcing by contrails (right) as functions of changes in mean cruise altitude. The results for the annual mean and for the boreal winter and summer seasons are displayed.

Contrail radiative forcing is not the only aviation climate impact; also NO_x emissions impact upon ozone (Grewe et al., 2002; Gauss et al., this issue), fuel consumption and, therefore, CO_2 emissions, impacts on cirrus clouds, and furthermore influence on air traffic management and flight endurance must also be considered to provide a reliable estimate of the overall effects of changing flight altitudes.

6 ACKNOWLEDGEMENTS

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Policies for Mitigating Contrail Formation from Aircraft

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Keywords: Contrails, Climate Policy, Carbon emissions

ABSTRACT: One possible approach to mitigating the production of contrails from aircraft is to place restrictions on cruise altitudes based upon ambient atmospheric conditions. This research examined the ability to restrict cruise altitudes as a policy for reducing contrail formation. A simulation model of European airspace was used to examine seasonal altitude restrictions and the effect on carbon emissions (fuel burn), travel times and air traffic controller workload. Seasonal altitude restrictions were based upon monthly average atmospheric conditions. Results showed only a small increase in carbon emissions and travel times but more severe implications for controller workload. Further analyses examined longer haul North Atlantic flights that would need more severe altitude restrictions. Potential further research and policy implications are discussed.

1 INTRODUCTION

Recent research is suggesting that the radiative forcing impact of contrail induced cirrus cloud formation may be significantly larger than the effect of carbon emissions and the effects of contrails alone (Mannstein, 2003). In addition, forecast growth in international air traffic suggests that this will be a growing problem. Given this rather bleak outlook on the climate impacts of increased air travel, this paper evaluates a potential solution that could rapidly eliminate contrail formation and the formation of associated cirrus clouds.

Specifically, we evaluate a strategy of restricting aircraft cruise altitudes such that aircraft operate under atmospheric conditions that do not result in persistent contrail formation. Contrail formation is sensitive to both ambient temperature and humidity levels in the atmosphere. These will tend to vary with altitude. In general, contrails are less likely to form at lower altitudes where temperatures are warmer, but also may be less likely to form at very high altitudes where humidity levels are low. For the most part, aircraft cruise altitudes are within a temperature and humidity band that is conducive to contrail formation.

The analysis presented here focuses on the implications of reducing aircraft cruise altitudes to avoid the super-saturated air masses that are most conducive to contrail formation. Increasing cruise altitudes may also represent a potential solution, but many uncertainties remain about the radiative impacts of water vapour emissions in the lower stratosphere. In addition, the implementation of such a policy would be restricted, as most aircraft cannot fly at the higher altitudes required. Furthermore, those capable would still need to pass through air masses where contrails would form, so the radiative impacts of contrail and associated cirrus would not be eliminated. For these reasons, we focus on the impacts of reducing cruise altitudes.

In the sections that follow, we first discuss the criteria used for selecting altitude restrictions. This is followed by an analysis of effects in European air-space, calculated using an air-space simulation model, and also calculations for longer-haul flights using estimates for specific aircraft type. Policy issues are then elaborated upon with a specific discussion of the issues associated with policy implementation. More detailed analysis can be found in Williams et al. (2002, 2003).

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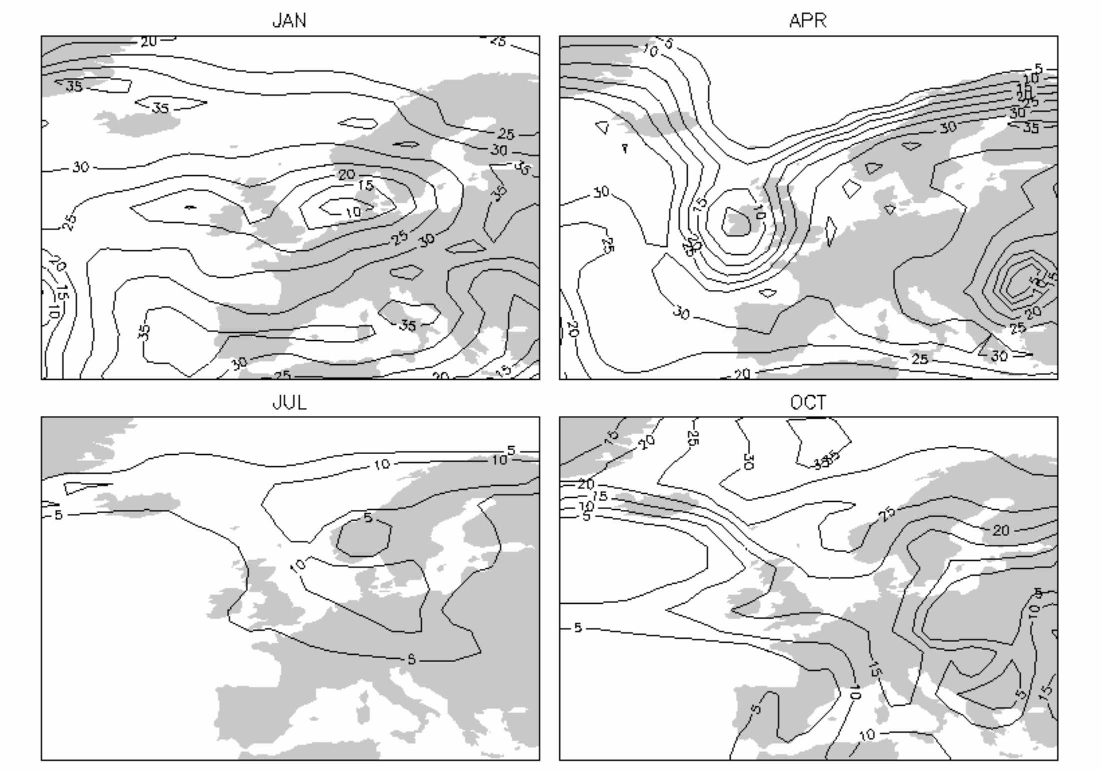

Figure 1: Potential contrail cover at an atmospheric pressure of 250mb

2 CALCULATION OF ALTITUDE RESTRICTIONS

In order to calculate the necessary altitude restrictions to minimize contrail formation it is first necessary to analyze atmospheric data to determine when and where contrails are likely to form. Calculations of the potential fractional contrail cover can be used to identify regions susceptible to contrail formation (Sausen et al. 1998). This is a measure of the maximum contrail coverage in a given area and is calculated from the mean atmospheric temperature and relative humidity over that area.

The NCEP/DOE AMIP-II Reanalysis (NCEP-II) dataset, which is a global analysis of atmospheric fields produced by assimilating land surface, ship, aircraft, satellite and other data, can be used to estimate potential contrail fraction. Using year 2000 monthly mean temperature and humidity data from NCEP-II data, on a range of atmospheric pressure levels spanning the range of flight cruise altitudes, we calculate potential contrail fraction using the method described by Sausen et al. (1998). Initially, maps of fractional cirrus cloud coverage were determined, using the parameterisation:

$$b_{Ci} = 1 - \left[\frac{1 - \max\left(U_i, U_{Ci}\right)}{1 - U_{Ci}} \right]^{1/2} \qquad (1)$$

where U_i is the relative humidity over ice and U_{Ci} is a threshold value (60%). Each point in the NCEP-II data represents an area of 2.5°x2.5°. This calculation determines the fraction (b_{Ci}) of that area covered by cirrus when the mean relative humidity over ice for that area is U_i. A modification of the cirrus cloud parameterisation was then used to calculate the combined coverage of cirrus cloud and contrail, allowing the additional contribution from contrail (the potential contrail fraction) to be evaluated. The contrail effect was incorporated by replacing U_{Ci} in (2) with a critical relative humidity value derived from the Smidt Appleman relation (Sausen et al.1998).

Figure 1 displays seasonal results for Europe for an atmospheric pressure of 250mb or around 10 km (33,000 ft) in altitude. As can be seen potential contrail coverage is significantly less prevalent during July and much greater in January. We then used this information to determine the flight level that matched only a 5% potential contrail fraction and derived a flight altitude ceiling on a monthly basis. This is shown in Figure 2 for Europe, the Northeastern US, and the North Atlantic. As can be seen, for the dataset analyzed, flight restrictions are much more severe for the latter two regions.

In all cases, one must keep in mind that the temperature and humidity data used to calculate contrail coverage is aggregated monthly mean data, on a 2.5°x2.5° spatial grid. Contrail coverage calculated from these monthly means may differ from the mean of contrail coverage calculated from daily or hourly data. It is likely that smaller levels of aggregation would lead to different results and that day-to-day variability may be substantial. This is important as it implies that altitude restrictions may in many cases be either more or less severe than those used in this analysis.

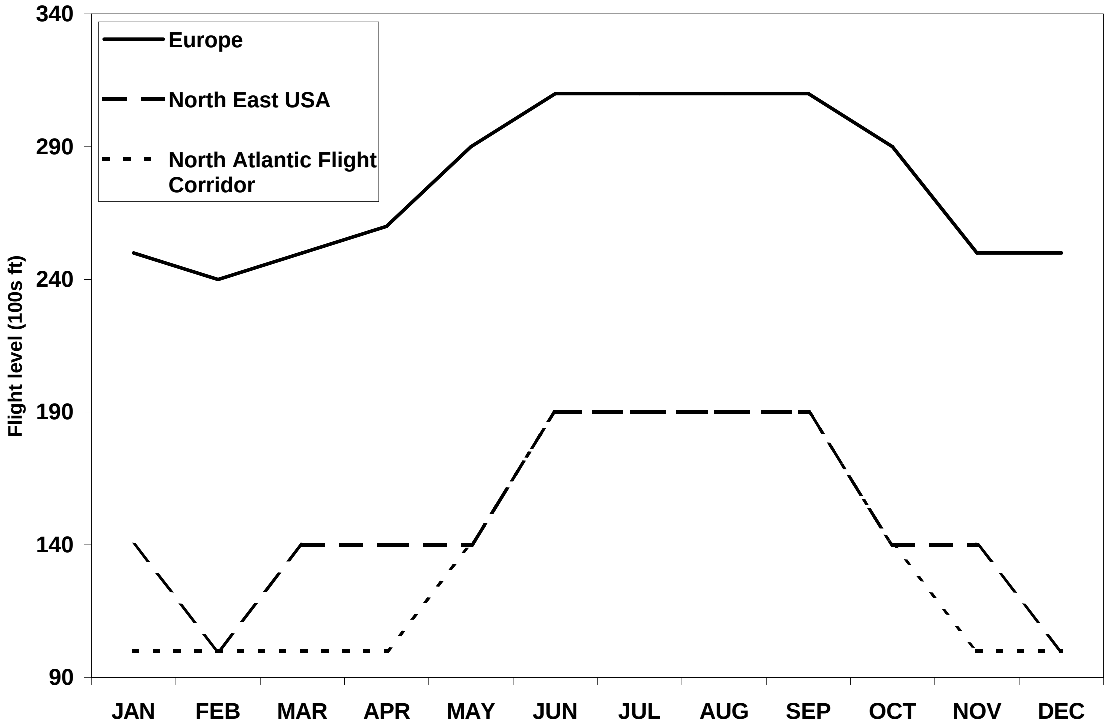

Figure 2. Seasonal variation in permitted flight levels for sectors of Europe, the Northeast USA, and the North Atlantic.

3 ANALYSIS OF IMPACTS

The impacts of restricting cruise altitudes were estimated using an airspace simulation model for European airspace and evaluation of aircraft performance data for longer haul flights. The simulation model used (the RAMS model) is widely used for management and planning of air traffic controller workloads. It provides a realistic simulation of the tasks initiated by air traffic controllers managing air traffic under congested conditions. An extended description of the model is provided in Williams et al. (2002).

This model was used to assess the impact of the altitude restrictions on fuel burn (i.e., carbon emissions), travel times, and controller workload. Fuel burn was calculated using Eurocontrol Experimental Centre base of aircraft data (BADA). Flight speed and rates of climb and descent were also specified using BADA performance tables. Over 71 aircraft types were included in the simulation which covered one day of air traffic on September 12, 1997. The region analyzed covered the "5-states" region of Europe, shown in Figure 3, which also shows the boundaries of the air traffic control sectors within the simulation.

To assess impacts on long-haul flights, we used BADA data to examine changes in fuel burn and travel time for various aircraft types and distances ranging from 3000 to 6000 nautical miles. Given the more severe altitude restrictions calculated for trans-Atlantic and Northeastern US (see Figure 2), we opted to evaluate these trade-offs at altitudes of 18,000 and 31,000 feet. These calculations are intended to be indicative of the scale of impacts associated with a contrail restriction policy on long haul flights, in contrast to the more detailed analysis presented for European airspace.

For both the European airspace and the long haul analysis, altitude restrictions are enforced for the duration of the flight. This may lead to an overestimation of impacts, particularly for the longest flights, which would be likely to pass through regions requiring less stringent restrictions.

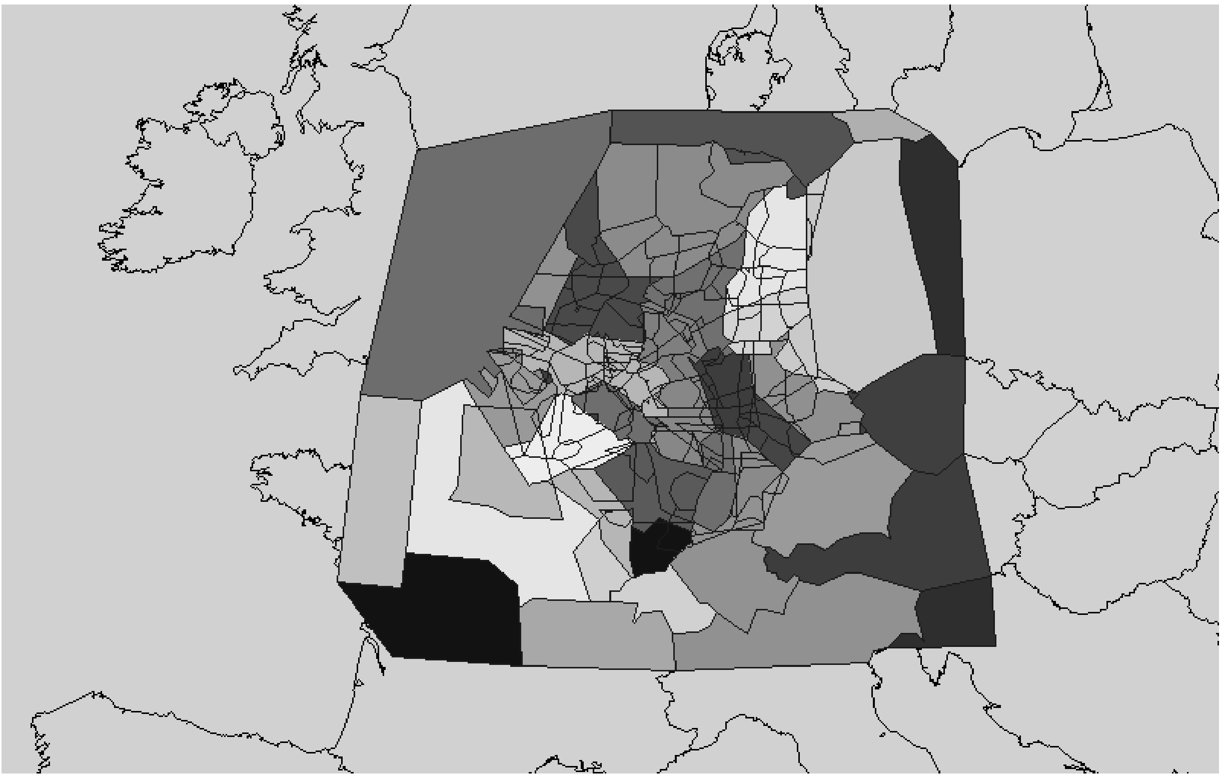

Figure 3. Coverage of the RAMS 5-states simulation. Air traffic control sector boundaries are marked.

3.1 *Fuel burn (carbon emission) impacts*

The impacts on fuel burn (i.e., carbon emissions) for the European simulations are detailed in Table 1. The total increase is only 3.9% over the unrestricted simulation. Given that this type of policy would virtually eliminate contrail formation (and associated cirrus clouds), the reduction in radiative forcing would not be off-set by the increase in carbon emissions.

Table 1. Change in fuel burn for European simulation.

Maximum flight level (in 100s of feet)	Months	% Change in fuel burn (compared to control simulation)
240	February	7.2
250	January, March, November, December	5.8
260	April	5.3
290	May, October	2.7
310	June, July, August, September	1.6
AVERAGE OVER YEAR		**3.9**

For long haul flights, estimated fuel burn is larger. With an altitude restriction of 18,000 feet this ranged from an increase of 20% for an Airbus 310 aircraft to as high as 60% for a Boeing 747-400. With a 31,000 feet altitude restriction, the increase ranged from about an 8% to 30% more fuel burn. Clearly a 60% increase in fuel burn may be less desirable, but even that may give a net reduction in radiative forcing, although this depends upon better knowledge of how to compare contrail and cirrus effects, which may only last a few hours, versus the many decades that carbon may remain in the atmosphere. The selection of aircraft is also critical and if this sort of policy were implemented, it is unlikely that those aircraft that suffer a large increase in fuel burn would still be flown under these conditions.

3.2 *Travel time impacts*

Travel time effects for the European simulation were found to be trivial. On average, travel times increase by less than one minute. The largest increase was about 17 minutes for one flight normally traversing the airspace at high altitude. The reason for this is that most of the flights within this sector are relatively short in duration and do not normally climb to high altitudes. Thus, the impacts of the altitude restrictions are relatively minor.

This is not the case for longer-haul flights. Again, travel time impacts were found to vary with the type of aircraft. For a distance of 6000 nm and an altitude of 18,000 ft, the Boeing 777-200 had an increased flight time of about 210 minutes. This is compared to the Boeing 747-200 with an increased flight time of only about 45 minutes. At an altitude restriction of 31,000 ft, some aircraft actually had about a 30 minute reduction in their flight time (due to less time spent in climb and descent modes).

These travel time increases may create some operational difficulties related to crew scheduling and even the feasible range of some flights. However, these differences are aircraft dependent and future design of aircraft could focus on optimising flight times at lower cruise altitudes, if this type of policy is desirable. In many cases, travel time increases of 30-60 minutes would probably be feasible.

3.3 *Controller workload effects in European airspace*

Previous studies have defined ‘severe’ controller workload in order to assess restrictions on airspace capacity. The definitions most commonly adopted are a total controller task time at or above 42 minutes (70%) in any one-hour period, or above 90 minutes (50%) in any three-hour period. These definitions of controller capacity are used to allow for controller actions such as the prioritisation of tasks, which are not directly specified in the controller task times.

Adopting the three-hour definition, the European simulations indicate that the imposition of cruise altitude restrictions would result in a dramatic increase in the number of sectors exceeding the threshold for capacity. In the control simulation, 7 sectors have a workload exceeding 50%. For the most restricted case, with maximum cruise altitudes constrained to 24,000ft, the total number of sectors in which the threshold is exceeded is 31.

Table 2: Number of conflicts for each air traffic control center, by altitude restriction

	Maximum permitted cruise altitude (100s feet)					
Air Traffic Control Center	**240**	**250**	**260**	**290**	**310**	**Control simulation**
AMSTERDAM	974	222	222	226	216	207
BREMEN	1353	133	137	138	144	137
CANAC	2108	305	307	304	299	310
DUSSELDORF	623	256	256	256	260	252
FRANKFURT	6071	606	626	586	583	587
KARLSRUHE	770	5407	5179	3883	3011	856
LUXEMBOURG	9	10	8	7	8	9
MAASTRICHT	0	4048	3828	2662	2176	902
PARIS	911	60	60	59	62	61
REIMS	510	1456	1390	1090	954	443
Total	13329	12503	12013	9211	7713	3764

An indication of the likely implications of the flight altitude restrictions on workload in each air traffic control centre can be obtained by considering the number of conflict events. At each triggered event in the model, such as a controller window entry, flight path trajectories within the controller window are compared to ensure that the required separation minima between aircraft are maintained. A violation of separation conditions is identified as a conflict and triggers the controller tasks necessary to determine a suitable resolution manoeuvre, such as a change in altitude for one of the aircraft in conflict. Each proposed resolution is checked against existing flight trajectories to avoid further separation violations. The total number of conflicts is found to increase with the severity of the altitude restriction applied, with the most restricted simulation having 3.5 times the conflicts as the unrestricted control simulation. The detail for each air traffic control center is shown in Table 2.

These effects on air traffic controller workload could be an impediment to implementation of an altitude restriction policy. However, this is primarily a function of the current design of air traffic control sectors, which are not optimised for the cruise altitudes which were simulated. For example, some high altitude sectors had no aircraft movements, while lower altitude sectors had a major increase in their traffic. Redesign of the existing air traffic control sectors could alleviate this problem.

4 CONCLUSIONS

This paper summarizes analysis previously presented in Williams et al. (2002, 2003). Results suggest that a policy of restricting aircraft cruise altitudes to levels where contrail formation does not occur, could be beneficial in reducing net radiative forcing. This is based upon average atmospheric conditions and disregards potential day-to-day variability in atmospheric conditions.

This suggests that a more attractive policy would be to require aircraft to avoid atmospheric air masses that are amenable to contrail formation by real-time flight planning. This would have the added benefit of minimizing the relatively small increases in carbon emissions in that selection of flight altitudes would not always require severe altitude restrictions, such as we examined for longer-haul flights.

Implementation issues are more problematic. Changes in flight journey times, while introducing various operational changes, are probably feasible. The key factor would be to select aircraft that both minimize journey time and fuel burn at the altitude that minimizes contrail production. Of more concern is the effect on existing air traffic control sectors. However, redesigning existing sectors to minimize climate impacts can probably alleviate this.

Further research in this area needs to explicitly examine the day-to-day variability in flight planning that would be necessary. The operational and cost impacts of this should also be evaluated (however, we imagine the cost to the airline industry would be significantly less than equalization of fuel taxes between transport modes). Finally, research needs to examine the best ways to redesign air traffic control sectors with the goal of minimizing environmental and climate impacts.

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Greener by Design

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Keywords: climate change, environmental impact of aviation, aircraft design, aircraft operations, aircraft emissions

ABSTRACT: Air Travel – Greener by Design is an initiative of the UK civil aviation community, embracing the aircraft and engine manufacturing industry, the airline and airport operators, the research community and government departments. Its primary objective is to identify and promote options for reducing the environmental impact of air travel. This paper considers what might be achieved within the next 50 years by advances in aircraft and engine technology and by a shift in design priority from minimising costs to minimising environmental impact. The emphasis of the paper is on climate change and it is suggested that, in the medium term, a substantial reduction in climate impact per passenger kilometre is potentially achievable. Present understanding of the effects of aviation on the atmosphere is, however, not yet sufficiently robust for this to be asserted with confidence. Atmospheric research, focussing on those effects of aviation which it may be possible to mitigate by design and operational changes, therefore remains a high environmental priority.

1 INTRODUCTION

In the coming century, the impact of air travel on the environment will become an increasingly powerful influence on aircraft design. Unless the impact per passenger kilometre can be reduced substantially relative to today's levels, environmental factors will increasingly limit the expansion of air travel and the social benefit that it brings. In the UK, the Air Travel - Greener by Design initiative is the response of the civil aviation community to this environmental challenge. Its participants are the main stakeholders in air travel - the aircraft and engine manufacturers, airline and airport operators, the research community and the appropriate government departments - and its primary objective is to assess and promote options for mitigating the environmental impact of aviation. More widely within Europe, the aeronautical research community has established the Advisory Council for Aeronautical Research in Europe (ACARE) and has set out a Strategic Research Agenda (ACARE, 2002) which gives high priority to, and sets ambitious goals for, reducing environmental impact.

Air Travel - Greener by Design established three sub-groups to study operations, technology and market-based options. This paper arises from the work of the Technology Sub-Group, of which the author is Chairman. The Sub-Group addressed the potential of technology and design to mitigate noise and air pollution around airports and to reduce the impact of air travel on climate change. It took 2050 as its time horizon, by when a fourfold increase in air traffic has been projected. The Sub-Group presented its first report in July 2001 and this was subsequently published in the open literature (Green, 2002). A later paper (Green, 2003) takes the discussion a stage further. The present paper draws on both these sources, focussing mainly on impact on climate change.

The paper considers briefly the potential role of regulation and economic instruments to mitigate environmental impact and the conflicts and trade-offs that arise, not only between commercial and environmental goals but also between different environmental goals. It then considers the main contributors to climate change, the challenges to technology that these present and the scope for reducing their impact by design and operational changes with today's technology standards. Finally, some conclusions are drawn and recommendations made for future research.

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2 REGULATION AND TRADE-OFFS

Aircraft noise and emissions in the vicinity of airports are subject to international regulation under ICAO. The regulations are established by international consensus and historically have followed rather than led the reductions in noise and emissions achieved over the past 30 years. For both noise and emissions, ICAO has adopted more stringent standards only when they have been shown to be economically achievable. Nevertheless, the technical measures needed to achieve the standards have entailed weight and performance penalties and the work to develop and validate them has added to aircraft first costs. Since the 1970s, therefore, noise and emission reductions have imposed some economic penalty on all new civil aircraft.

In parallel with international regulation, local variants have emerged which override the ICAO rules. An example is the system of noise quota counts imposed by the UK Government for night-time operations from the three London airports. In response to this, the customers for the Airbus A380 have required the aircraft to meet approximately the same noise certification standards as the A340, an aircraft half the size. This demanding target has resulted in an engine of larger than optimum diameter and a consequent fuel burn penalty of the order of 1% to 2%, depending on range.

Concern about the impact of aviation on climate change is a relatively new phenomenon, lagging more than a decade behind concern about emissions in the vicinity of airports and two decades behind concern about noise. The Kyoto Protocol of 1997, which committed signatories to cutting greenhouse gas emissions by 12.5% of 1990 levels by 2012, explicitly excluded international aviation but, even so, the contribution of aviation to climate change has become increasingly prominent in the public eye. While there is as yet no ICAO regulation in this field, the subject is being considered by the ICAO Committee on Aviation Environmental Protection (CAEP). Other bodies, notably the European Union and the UK Government, are also considering possible financial incentives in the form, for example, of a tax or levy on aviation fuel

In a recent consultation paper, issued jointly by the UK Department of Transport and the Treasury (Department for Transport, 2003), estimates were given of the annual external costs of the environmental impact of UK civil aviation, as follows:

Noise	£25m
Local air quality	£119m - £236m
Climate change	£1,400m

The origins of these figures are set out in the reference. It is interesting to note that, although the external cost of air pollution around airports is estimated to be some five to ten times the cost of noise, complaints from the public about aircraft noise vastly exceed complaints about the effect of aircraft on air quality. The key point about these figures is that they lead to the conclusion in the paper that, “Aviation’s principal externality, which can be translated into monetary terms, arises from the effects of greenhouse gases and the impact they have on climate change.” This was also the view of the Technology Sub-Group and is the underlying theme of this paper.

There are, however, conflicts and trade-offs between commercial and environmental goals which complicate the picture. For example, the requirement cited above that the Airbus A380 should meet particular night time noise quota count levels entailed an increase in fuel burn which will increase not only operating costs but also CO_2 emissions. A more powerful conflict arises in engine design, where measures to increase engine thermal efficiency in order to reduce fuel burn and CO_2 emission result in increased NO_x emissions. Because NO_x emissions impact not only on air quality around airports but also on climate change, the trade off between NO_x and CO_2 emissions raises questions which have not yet been considered by the engine designer, whose focus is on commercial optimisation of the engine. A further example of conflict is raised by the possibility of reducing aircraft cruise altitude in order to reduce the risk of generating contrails, which have a powerful greenhouse effect, but thereby increasing fuel burn, operating costs and CO_2 emissions. These various conflicts have an important bearing on the technological and design compromises needed to achieve an appropriate balance between environmental and commercial goals. They also have a bearing on the form of regulation and economic instruments best suited to minimising environmental impact. In particular, they lead to the conclusion that measures such as levies on fuel, designed solely to reduce CO_2 emissions, are unlikely to achieve the best environmental outcome.

3 CONTRIBUTION OF AVIATION TO CLIMATE CHANGE

The various emissions from aircraft flying at altitude contribute to climate change through a range of different chemical and physical processes. Until the new evidence now emerging (some of which has been presented at the AAC Conference) has been fully assessed, the best available quantification of the effects of these processes is generally accepted to be that presented in "Aviation and the Global Atmosphere" (IPCC, 1999). For 1992, the IPCC estimate of the percentage contributions to the total radiative forcing due to aviation, rounded to the nearest 0.5%, and the assessed quality of the estimates of the individual components, are:

Contributor	percentage	quality of estimate
Carbon dioxide	+ 37.0	good
Ozone	+ 47.5	fair
Methane	- 29.0	poor
Water	+ 3.0	poor
Contrails	+ 41.5	fair
Cirrus cloud	not estimated	very poor
Sulphate aerosols	- 6.0	fair
Black carbon aerosols	+ 6.0	fair

The increase in ozone and decrease in methane are both the result of NO_x emission, the net effect of which is to contribute positively to radiative forcing. It is argued, however, that the two effects cannot be simply added to give a net contribution to radiative forcing. Because methane is a long-lived gas whilst ozone, and the NO_x which generates ozone and destroys methane, are short lived, the negative greenhouse effect of the methane destruction tends to be distributed globally whilst the effect of the ozone creation is localised around the main flight corridors and may thus have a greater effect on climate than represented by the overall impact on radiative forcing given in the table.

In 1999, the uncertainty about cirrus cloud generated by aircraft was considered too great to justify the inclusion of an estimate of the effect of aviation-induced cirrus cloud in the total estimate of radiative forcing. The uncertainty range in 1999 did, however, put the effect between 0% and 80% of the total forcing from all other sources, suggesting that it might well be a significant contributor, coupled to contrails. In this conference, Mannstein has presented evidence that the combined effect of persistent contrails and the cirrus cloud which develops from them may well constitute the greatest single contribution of aviation to climate change.

On the basis of the above table, three main contributors of aviation to climate change can be identified.

They are CO_2, NO_x and persistent contrails with their consequent cirrus. In the following sections we consider what might be done, by technological advance and changes in design and operation, to reduce the impact of these three. It will be argued that, in the medium term, reducing the impact of contrails and NO_x offers the greatest potential. Before doing so, however, it is appropriate to consider the lives in the atmosphere of the main greenhouse gases as shown in the following table (Rogers et al., 2002).

Carbon dioxide	50 - 100 years
Methane	8 - 10 years
Water	days (sea level) weeks (tropopause)
Ozone	week (sea level) months (tropopause)
NOx	days (sea level) weeks (tropopause)

The conclusion to draw from this table is that, even if in the short and medium term contrails and NO_x are potentially the more rewarding targets, in the long term action to reduce CO_2 emissions is also essential. Although this is the most challenging of the three targets, the work of the Greener by Design Technology Sub-Group identified technologies by which substantial reductions in CO_2 emissions could be achieved, provided radical changes to aircraft design concepts are adopted.

4 CHALLENGES TO DESIGN AND TECHNOLOGY

In this section the three main contributors are considered in turn. Measures to reduce each, by changes in operating procedures, design and technological advance are discussed and the implications, if any, for the other contributors is noted.

4.1 *Reducing persistent contrails and cirrus cloud*

The atmospheric conditions under which contrails form are reasonably well understood (Lee et al., 2000), as are the conditions under which they quickly evaporate again. In order for contrails to persist and, with time, be distorted and dispersed by wind shear to form cirrus cloud, the air within the contrail, when the engine exhaust is extensively mixed with the ambient air, must be saturated or supersaturated with respect to ice. However, because an engine adds heat as well as water vapour to the air mass, the critical conditions of temperature and humidity for a contrail to persist depend on the propulsive efficiency of the engine. As engines have become more efficient, mean exhaust temperatures have fallen and the temperature-humidity boundary for the creation of a long lived contrail has moved upwards, so that contrails are found in warmer air today than in the 1970s.

Lee et al. observe that there is no current or envisaged technology that will inhibit the formation and persistence of contrails. If a kerosene-fuelled aircraft flies through an ice-saturated air mass, contrails will form and persist. That said, ice saturation tends to occur in defined volumes of cold, relatively humid air which have been characterised as “moist lenses” (Gierens et al., 1997). These have a maximum vertical extent of a few kilometres and a maximum horizontal extent of about 1,000km, the precise extent for a particular air mass depending on engine propulsive efficiency. As Lee et al. note, an individual lens could be avoided by flying under it, over it or around it.

Since aircraft generally fly at their most economical altitude, taking evasive action by flying higher or lower than optimum, or by making a detour to avoid saturated air, will increase fuel burn, cost and CO_2 emission. On the other hand, in addition to reducing contrail formation, flying lower might also reduce the impact on climate of NO_x emissions (Klug et al., 1996). Overall, the environmental benefit of avoiding contrails, particularly if coupled with a reduction in the impact of NO_x, seems likely to outweigh by a considerable margin the effect of increased CO_2 emission.

It would be premature to recommend evasive action as an operational procedure at this stage. The basic scientific understanding is not sufficiently robust. Neither air traffic management nor meteorological forecasting are currently well placed to support such a procedure. The possible impact of changes in flight altitude on the impact of NO_x emissions is not well understood. Evasive action would increase fuel burn, CO_2 emission and airline costs. Nevertheless, the recent evidence on cirrus presented at the AAC Conference by Mannstein suggests that a strategy of contrail avoidance could be a powerful way of reducing the impact of air travel on climate change, even though it would entail a small increase in CO_2 emissions. The possibilities of such a strategy merit more detailed investigation.

4.2 *Reducing the impact of NO_x*

NO_x emissions in the vicinity of the airport are already the subject of regulations drawn up by the ICAO Committee on Aviation Environmental Protection (CAEP). These regulations make allowance for the fact that, as engine overall pressure ratio is increased in order to achieve higher thermal efficiency and hence reduced fuel burn and CO_2 emission, the increased temperatures and pressures in the combustor lead to increased NO_x production. For example, the regulation currently in effect, CAEP-2, allows NO_x emission to increase by about one third for an increase in engine pressure ratio from 25 to 40. The best in-service combustor technology gives NO_x emissions appreciably below the CAEP-2 line but show a rather steeper variation with pressure ratio. Between these two pressure ratios, actual NO_x emissions for this class of combustor increase by a factor of 2.25. The corresponding increase in thermal efficiency gives a reduction in fuel burn of slightly less than 9%.

There are substantial research programmes in Europe and the United States aimed at low NO_x combustor technology. Although these are currently aimed at emissions in the vicinity of airports, any advances which reduce emissions here should also produce some reductions in emissions at cruise. Ambitious targets have been set for this research but the evidence to date suggests that success is more likely at the medium pressure ratios of small engines than at the high pressure ratios of the large engines typical of long-range aircraft.

Besides the pursuit of more advanced combustor technology, the avenue of reducing NO_x emission by reducing engine pressure ratio is worth exploring. In the report of the Greener by Design Technology Sub-Group (Green, 2002), one recommendation was that a study should be made of the methodology of designing engines to minimise impact on climate rather than minimising fuel burn. This recommendation was taken up as part of a study of propulsion system optimisation (Whellens and Singh, 2002). The starting point was a baseline engine typical of a large, long-range aircraft, optimised for minimum fuel burn at cruise. An engine with the same thrust at cruise but optimised for minimum impact on climate had a substantially lower overall pressure ratio (11.5 as against 44 for the baseline engine) and lower turbine inlet temperature (1.300K as against 1,555K). The resulting impact on climate was estimated to be 46% lower than that of the baseline engine, but at an unacceptable fuel burn penalty of 21%. However, for a fuel burn penalty of only 5%, the estimated reduction in impact on climate was still between 30% and 40%.

This work employed a model of the effect of NO_x emissions on climate (Klug et al., 1996) which employed Global Warming Potential (GWP) as a metric for impact on climate. This metric is not now favoured by the atmospheric science community. The modelling by Klug et al. of the variation with altitude of the effect of NO_x also makes use of GWP and is therefore subject to the same reservations. Nevertheless, the trends found by Whellens and Singh are clearly qualitatively correct and the variation with altitude of the effects of NO_x, at altitudes around the tropopause, are also likely to be qualitatively similar to those derived by Klug et al. Clearly, advances in atmospheric science are needed to provide a more solid basis for assessing the environmental effects of NO_x and particularly their variation with altitude. Future aircraft and engine design could be significantly influenced by this knowledge.

4.3 *Reducing CO_2 emissions*

Reducing CO_2 emission equates exactly to reducing fuel burn. The appropriate cost/benefit metric is fuel burn per passenger kilometre. From a derivative of the well known Breguet range equation (Green, 2002), an expression for this metric can be written

$$W_{MF}/RW_P = (1 + W_E/W_P)(1.022\exp(R/X) - 1)/R \qquad (1)$$

where W_{MF} is the mission fuel burned between engine start up and shut down, W_P is the payload, W_E the empty weight, R the range and X a range performance parameter defined by

$$X = H\eta L/D \qquad (2)$$

where H is the calorific value of the fuel, η is the overall propulsion efficiency of the engine and L/D is the lift-to-drag ratio of the aircraft at cruise. It is usual to express H in Joules/kg but, since this has the dimension length, H can also be expressed in km. Then, since η and L/D are dimensionless, X can be expressed in km. For a kerosene-fuelled medium or long-range aircraft swept-winged aircraft with currently achievable values of η and L/D, X is approximately 30,000 km.

If aircraft range and payload are specified, Equation 1 shows that the only ways of reducing fuel burn per passenger kilometre are to reduce the ratio of empty weight to payload and to increase the value of the range parameter X. For kerosene-fuelled aircraft H is effectively fixed, leaving propulsion efficiency ? and lift to drag ratio L/D as the only two variables which can be increased to increase X. The potential for reducing fuel burn by reducing empty weight and increasing propulsion and aerodynamic efficiency are now discussed in turn.

4.3.1 *Reducing CO_2 by reducing empty weight*

There is scope for reducing aircraft empty weight through the greater use of lightweight materials. In general this entails a cost penalty and the uptake of materials such as carbon fibre reinforced plastic (CFRP) has consequently turned out to be rather less than was forecast in the 1980s. For example, on the Airbus A330 and the Boeing 777, CFRP accounts for some 15% of the structure weight, as compared with “conservative” and “optimistic” forecasts of 25% and 65% respectively made in the mid 1980s (Peel, 1996). Cost will continue to be an inhibiting factor but the proportion of civil aircraft structure made from specialised lightweight materials can be expected to increase over the coming years.

The potential for reducing weight by more efficient structural design must be limited for aircraft of the classical swept wing configuration, which has been evolving for more than 50 years. New manufacturing technology may lead to some weight saving, however, and a new configuration, such as a blended wing-body, would also have lower structural weight. Other potential developments, such as the More Electric Aircraft, should also yield weight reductions. Taking all potential advances together, the Greener by Design Technology Sub-Group (Green, 2002) projected a reduction of 15% in the empty weight of a classical swept-winged aircraft design by 2050. This would reduce the first term on the right-hand side of Equation 1, and hence fuel burn per passenger kilometre, by approximately 10%.

This term in Equation 1 can also be influenced by design parameters such as cruise Mach number and design range. Reducing cruise Mach number enables wing sweep to be reduced and/or wing thickness to be increased, thereby enabling wing weight to be reduced. Although today’s aircraft are designed to be close to minimum fuel burn, it is probable that some reduction in fuel burn could be achieved by designing for a lower cruise Mach number. Whilst cruise Mach number has a relatively weak effect, this is not the case for design range. A comparison between two paper swept-winged aircraft designed to carry the same payload over ranges of 5,000km and 15,000km (Green, 2002) suggests that the empty weight of the long range aircraft is more than 40% greater than that of a medium range aircraft designed to carry the same payload. As a result, the first term on the right-hand side of Equation 1 is 22% smaller for the medium-range aircraft than for its long- range equivalent. The fuel benefit of the weight reduction associated with the change from a long-range to a medium-range design is approximately twice the benefit from the weight reduction that might be achieved by 50 years of technological advance.

4.3.2 *Reducing CO_2 by increasing overall propulsion efficiency*

Overall propulsion efficiency can be written

$$\eta = \eta_E \eta_P \tag{3}$$

where η_E is the thermal efficiency of the gas turbine and η_P is the propulsive efficiency of the jet. For the classical Joule or Brayton cycle for gas turbines, thermal efficiency η_E can be increased by further improvements in the aerodynamic efficiency of the compressor and turbine and by increasing the thermal efficiency of the basic cycle. The latter requires increasing both the engine overall pressure ratio and turbine entry temperature and hence, for a given standard of combustor technology, increasing NO_x emission. Although this route of increasing pressure and temperature is the one which engine design has been following for the past 50 years, for reasons set out more fully elsewhere (Green, 2002 and 2003) it is thought environmentally not to be an appropriate way forward.

The second component η_P in Equation 3 is the propulsive efficiency of the jet, sometimes known as the Froude efficiency. For the engine in isolation, η_P reduces monotonically as the specific thrust (net thrust divided by total air mass flow through the engine) is reduced or bypass ratio increased. However, it is found (Birch, 2000) that, because engine weight and nacelle drag increase as engine diameter is increased to reduce specific thrust, today’s large engines are close to the economic optimum in terms of fuel burn, weight and operating costs. Further reduction in specific thrust increases Froude efficiency but, because of its side effects, also increases fuel burn. Consequently, if further increases in engine pressure ratio and turbine entry temperature are resisted for environmental reasons, there seems to be little prospect of a significant increase in the overall propulsion efficiency of conventional turbofan engines above the best of today’s levels.

In the Greener by Design studies, two alternatives to the conventional turbofan were considered (Green, 2002). The first was the inter-cooled recuperative (ICR) turbofan engine cycle, in which the compressor flow is cooled part-way through compression by heat exchange with the fan stream and then heated at the end of compression by heat exchange with the turbine exhaust (Plohr et al., 1999). At the expense of considerably increased weight and complexity, the cycle is predicted to yield a

higher thermal efficiency and potentially lower NO_x emission than a conventional turbofan of the same thrust. The components of the ICR engine are the subject of an EU technology programme.
The second alternative to the turbofan was the advanced contra-rotating propeller or unducted fan system. This has an appreciably lower specific thrust than today's turbofans but avoids the fan- cowl weight and drag penalties of the turbofan. It was extensively studied in the late 1980s and shown to be a practicable system for aircraft with cruise Mach numbers up to approximately 0.8. Concerns about first cost, maintenance, noise and safety, combined with the relatively low cost of fuel and hence low savings in direct operating costs, led to it being shelved. As a candidate for future aircraft, it is not suitable for installation on low wings and would be limited to rear-engined, high winged or possibly flying wing configurations. It remains nevertheless one of the few identifiable technologies which could achieve a significant reduction in fuel burn for all classes of aircraft where a limitation of cruise Mach number to around 0.8 is acceptable.

4.3.3 *Reducing CO_2 by reducing drag*

In Equation 2, with H effectively constant, the second variable which influences fuel burn per passenger kilometre is L/D, the lift-to-drag ratio. Since in 1g flight lift is equal to aircraft weight, the technological challenge is to reduce aircraft drag for a given weight of aircraft. For the classical swept-winged aircraft with underslung turbofan engines, this is a stern challenge. The first aircraft of this configuration was the Boeing B-47 Stratojet, which first flew in 1947. After more than 50 years of development, this configuration is now highly refined aerodynamically and the scope for further improvement is small. To achieve a significant reduction in drag and fuel burn, some more or less radical departure from the classical aircraft is needed.

The Greener by Design technology report (Green, 2002) presented the results of a study of a set of 13 different aircraft, ranging from a long-range kerosene-fuelled swept-winged aircraft typical of today's large aircraft to a hydrogen-fuelled flying wing with all-over laminar flow control and unducted fan propulsion. To illustrate the effects of introducing new technology, the projected reduction in fuel burn per passenger kilometre is shown below for a more limited set of aircraft. The baseline is a classical swept-winged aircraft with a design range of 5,000km. The first variant is a similar aircraft with hybrid laminar flow control (HLFC) applied to the wing, empennage and nacelles by suction through fine holes in the surface over the forward parts of the treated components. Next is the widely discussed blended wing-body, without laminar flow control. Third is a flying wing, based on a design study by Handley-Page in the 1960s (Lachmann, 1961), which achieves all-over laminar flow by the all-over application of surface suction. All four of the above aircraft have turbofan engines. The fifth variant is the laminar flying wing with unducted fan propulsion.

configuration	design range km	%fuel burn reduction
swept wing, medium range	5,000	-
swept wing, medium range with HLFC	5,000	16.5
blended wing-body	6,000	19.6
laminar flying wing	9,000	51.5
laminar flying wing with unducted fan	9,000	57.2

The reductions in this table for the two medium term technologies, hybrid laminar flow control and the blended wing-body, are greater than any advances that might be expected in the medium term from either weight reduction through wider use of lightweight materials or improvements in propulsion efficiency, including the introduction of unducted fan propulsion. Beyond that, the all laminar flow flying wing offers a really substantial reduction in fuel burn. Drag reduction appears to be by far the most potent technology available for reducing CO_2 emission by civil aircraft.

4.3.4 *The significance of range*

In the preceding discussion of Equation 1, the effect has been considered of varying empty weight and the range performance parameter X with payload and range R held fixed. As is evident from the equation, however, range has a strong influence on fuel burn per passenger kilometre. For swept-winged aircraft of today's technology standard, it is found (Green, 2002) that the most fuel efficient design range is about 4,000km: aircraft with a design range of 15,000km are appreciably less fuel efficient. This observation led to the thought that it might be more fuel efficient to undertake long-range journeys in a series of stages of around 4,000km rather than in a single stage. To illustrate the point, the table below compares the aircraft and fuel burn needed to carry a given payload over a distance of 15,000km in a single stage in a long range aircraft and in three stages of 5,000km in a medium range aircraft.

design range [km]	payload [tonne]	stage fuel [tonne]	take-off weight [tonne]	empty weight [tonne]	total fuel [tonne]
15,000	44.8	120.4	300.0	134.8	120.4
5,000	44.8	28.6	169.0	95.6	85.8

The aircraft needed to make the journey in a single stage has an empty weight some 40% greater than the medium-range aircraft and requires 40% more fuel to complete its task. Its take off weight is nearly 80% greater and its noise levels will be correspondingly higher. Its capital and running costs will also be higher. The Greener by Design technology report recommended that a full system study should be made of undertaking long distance travel in a series of shorter stages. A maximum stage length of 7,500km was suggested.

Although the Greener by Design study focussed primarily on medium and long range aircraft, it is important not to lose sight of the fact that more than half the aviation fuel burned is on flights over less than 3,000km, much of it in smaller aircraft for which the more radical flying wing configurations are not credible candidates. The future potential for reducing fuel burn over the shorter ranges is not very great. The introduction of hybrid laminar flow control, unducted fan propulsion and structural weight reduction are the three most promising technologies for this class of aircraft. In addition, reducing NO_x and contrails are important objectives for short and medium range travel, just they are for the longer ranges.

4.4 *Design and operational questions*

Although the preceding sections have focussed on the potential for reducing impact on climate through technological advance, it appears that the potential for reducing this impact by changes in design philosophy and in operational procedures is no less important. Some key questions are:

- Can contrail formation be reduced by adjusting flight paths to avoid regions of ice-saturated air, what is needed by way of meteorological information and air traffic management systems to achieve this, what would be the net effect on climate change, allowing for the consequent increase in CO_2 emission, and what would be the economic cost to the airlines?
- Within reasonable commercial limits, what is the potential for reducing overall impact on climate by designing engines which have lower overall pressure ratio and consequently lower NO_x emissions but higher specific fuel consumption and CO_2 emissions?
- Would reducing cruise altitude significantly reduce the impact of NO_x?
- What would be the environmental, commercial and operational consequences of progressively replacing long-range aircraft by medium range ones and undertaking long-distance journeys in two or three stages?
- What would be the effect of reducing cruise Mach number (a) for turbofan powered aircraft and (b) to enable a transition from turbofan to unducted fan propulsion?

Underlying these questions is the broader one of how to develop a methodology for designing for minimum environmental impact rather than for minimum operating costs and, beyond that, how to strike the best balance between environmental and commercial objectives.

5 CONCLUSIONS AND RECOMMENDATIONS

1) In the long term, impact on climate is the most important environmental effect of aviation.

2) Reducing persistent contrails and NO_x are probably the two most potent means of reducing this impact: in each case, the best environmental result is likely to entail some increase in CO_2 emissions.
3) Because CO_2 is such a long-lived greenhouse gas, reducing its emission is a key long term goal: drag reduction is the most potent technology but weight reduction and adoption of the unducted fan to increase propulsion efficiency can also contribute. Aircraft design parameters – design range, cruise altitude and cruise Mach number are also significant factors.
4) To achieve large reductions in CO_2 emission will require radical aircraft design changes – the adoption of laminar flow control technology and, for large aircraft, a change to the flying wing or blended wing-body configuration.
5) Regulatory and economic measures should be framed so as to promote the greatest possible reduction in impact on climate: measures aimed solely at reducing CO_2 emission will probably do more harm than good.
6) In research, the most immediate priority is to continue to strengthen understanding of the effects of aviation on the atmosphere.
7) In technology, demonstration of the practicability of hybrid laminar flow control in airline service is a priority. Demonstration of practicable ultra low NO_x combustion technology at realistic engine pressure ratios is also urgently needed. Among more radical concepts, demonstration of the practicability of the ICR engine cycle and the blended wing-body layout are also needed and, looking further ahead, the all laminar flying wing merits re-examination.
8) In design, methodologies for designing to minimise environmental impact and for balancing environmental and commercial objectives need to be developed. Multi-segment long-distance travel also merits a full system study.
9) The challenge to technology and design is severe. The timescales for introducing new technology and new design concepts are long. The need for research and demonstration is urgent.

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Climate responses to aviation NO_x and CO_2 emissions scenarios

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ABSTRACT: The linear climate response model of Sausen and Schumann (2000) was used to further investigate the changes of global mean surface temperature and sea level in response to emissions of aviation CO_2 and NO_x. The parameters of the model were reviewed in the light of more recent data so that it represented mean climate model responses reported in the IPCC's Third Assessment Report, rather than the original parent climate model, ECHAM3. As in its original formulation, aviation emissions of NO_x and CO_2 resulted in a greater temperature increase from O_3 forcing than for CO_2. As a result, the CO_2 temperature response increased by 70% and the O_3 response by 58% because of the increased temperature response of a doubling of CO_2. The main sensitivity of the model remains as identified previously: the value of the equilibrium surface temperature response of O_3 from aviation NO_x emissions, further assessments of which are needed. A new global aviation emission scenario was investigated with the newly parameterized model, based upon recent industry information that suggests that the fleet global emission index for NO_x may be reduced some 10 years earlier than previously estimated. This resulted in a smaller O_3 response of 20% by 2050, when compared with the original (non NO_x-aggressive) scenario. It is recommended that the model should be further developed so that a more complete picture of climate responses can be obtained.

1 INTRODUCTION

Aircraft emissions may influence climate by a number of emissions and effects, as has been shown in detail in the report of the Intergovernmental Panel on Climate Change (IPCC) 'Aviation and the Global Atmosphere' (IPCC, 1999). Gas turbine engines burning kerosene emit a number of trace gases and particles and can trigger the formation of contrails and cirrus clouds. Amongst the emitted species, carbon dioxide (CO2) is formed at a constant ratio to the fuel consumed; emissions of nitrogen oxides (NOx=NO2+NO) result in the formation of ozone (O3) and destruction of a small amount of methane (CH4) – a climate warming gas that comes from other sources. Particles may have direct warming or cooling effects, depending upon their composition, but in combination with emitted water vapour may also trigger the formation of contrails, which if persistent can have a warming effect as can any subsequent cirrus cloud formed.

The degree to which aircraft emissions affect climate is measured with the climate metric, radiative forcing. This metric has been adopted by the IPCC and the scientific community at large because of its usefulness in assessing different effects on climate. The radiative forcing concept has both strengths and weaknesses (Shine and Forster, 1999; Fuglestvedt *et al*., 2003), particularly in the context of some aviation effects. Radiative forcing of climate occurs when an agent disturbs the radiative balance of the Earth's atmosphere: when the atmosphere is perturbed it re-establishes radiative equilibrium with a consequential warming or cooling of climate, depending upon the nature of the climate forcing agent.

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For the past three decades or more, aircraft engine manufacturers and research agencies have put considerable effort into developing technologies that reduce the fuel consumption and NO_x emissions of aircraft. Engine technology has now advanced so far that in order to further reduce fuel consumption and, as a consequence, CO_2 emissions, overall engine pressure ratios may increase further. As a result of the higher temperatures and pressures, NO_x emissions become more difficult to reduce. The radiative forcings (RFs) for CO_2 and O_3 from aviation for 1992 were not greatly dissimilar; 0.018 and 0.023 W m^{-2}, respectively (IPCC, 1999). However, using a climate response model, Sausen and Schumann (2000) found a greater environmental response in terms of a globally-averaged increase in surface temperature from O_3 than from CO_2. Thus, there are two potential tradeoffs; the engine technology CO_2 vs NO_x trade-off and the CO_2 vs O_3 global temperature response trade-off. Simple climate response models such as that of Sausen and Schumann (2000) – hereafter S&S – may be used to perform climate simulations that allow efficient exploration of emissions scenarios, particularly where the climate response is small and the necessary integration time is long.

In this study, we use the S&S model to further explore aviation emission scenarios that help to target where emissions reductions may best ameliorate climate impacts. The model is updated based on recent estimates of climate parameters from the IPCC's Third Assessment Report – or TAR – (IPCC, 2001), so that a 'generalized response model' is formulated and the results compared with the original form of the model, which is based upon the performance of ECHAM3/LSG, its parent GCM. Further, updated technology information from the aviation industry is used to formulate a simple further global scenario of NO_x emissions. Finally, recommendations are made for further study and model development.

2 MODEL DESCRIPTION AND STUDY DESIGN

The S&S (2000) linear response model takes the form of a convolution integral that predicts CO2 concentration, CO2 radiative forcing (RF), normalized RF from O3 (from aircraft NOx) and the resultant changes in global mean surface temperature and sea-level. The model is 'tuned' to perform similarly to its parent GCM, ECHAM3/LSG. A full description of the model and its parameters may be found in S&S (2000). Here, a generalized version of the model was formulated that approximates to a mean response of GCMs used in the TAR, rather than being ECHAM-specific. The TAR mean temperature response to a CO2 doubling was 3.8 K (cf 2.246 K from ECHAM3/LSG); and the RF from CO2 in the TAR was estimated to be 1.46 W m-2 (cf 1.56 W m-2 from IPCC Second Assessment Report). The mean sea-level rise for a doubling of CO2 was not changed, despite the higher value that was given by TAR.

The emissions scenarios utilized include 'Fa1' and 'Fa2' from the IPCC (1999) aviation scenarios formulated for the IPCC by FESG (1998) using ICCAIA (1997) technology trend scenario data. These emissions data spanned 1992 to 2050. Data prior to 1992 were taken from the estimations of S&S (2000).

The Fa1 and Fa2 scenarios have an underlying GDP growth rate taken from the IS92a scenario. The descriptors '1' and '2' refer to the two technology scenarios, TS1 and TS2, which considered different technology trends. In TS1, it is assumed that fuel efficiency of production aircraft in 2050 will be some 40 – 50% better than 1997, and that the fleet average LTO NO_x will be 10 – 30% below CAEP/2 limits by 2050. In TS2, it is assumed that the emphasis is on NO_x, rather than fuel efficiency, with fuel efficiency of production aircraft in 2050 will be some 30 – 40% better than 1997, and that the fleet average LTO NO_x will be 50 – 70% below CAEP/2 limits by 2050. In this study, an additional scenario has been formulated, denoted 'Fa3', based upon an ICCAIA report (ICCAIA, 2000) that suggested that NO_x levels might be reduced some 10 years earlier than suggested by the original ICCAIA (1997) work for the IPCC. As a simple first case assumption, the existing ICCAIA technology scenario 2 (for ambitious NO_x reductions) was modified such that the fleet $EINO_x$ reduced by the same incremental amount, but at an earlier starting date by 10 years. This assumption also results in lower peak fleet $EINO_x$ values.

3 RESULTS

3.1 *Model sensitivity to generalized parameters*

The model was run in two modes, 'TAR' and 'ECHAM3/LSG', which refer to the generalized model based upon TAR mean GCM parameters and the original formulation, respectively. Simulations were run in both modes and example output is given at the time horizon, 1990 in Table 1 below.

Table 1 Comparative results and percent change for ECHAM and TAR model modes

Simulation	Time horizon, 1990
Fa1 RF (W m^{-2}) ECHAM3/LSG	0.0215
Fa1 RF (W m^{-2}) IPCC TAR	0.0201
	-6.5%
Fa1 ΔT (K) CO_2 ECHAM3/LSG	0.0037
Fa1 ΔT (K) CO_2 IPCC TAR	0.0063
	+70%
Fa1 ΔT (K) O_3 ECHAM3/LSG	0.019
Fa1 ΔT (K) O_3 IPCC TAR	0.032
	+58%
Fa1 Δh (cm) CO_2 ECHAM3/LSG	0.037
Fa1 Δh (cm) CO_2 IPCC TAR	0.037
	No change

The evolution of changes in global mean surface temperatures according to the two model formulations are shown in Fig. 1.

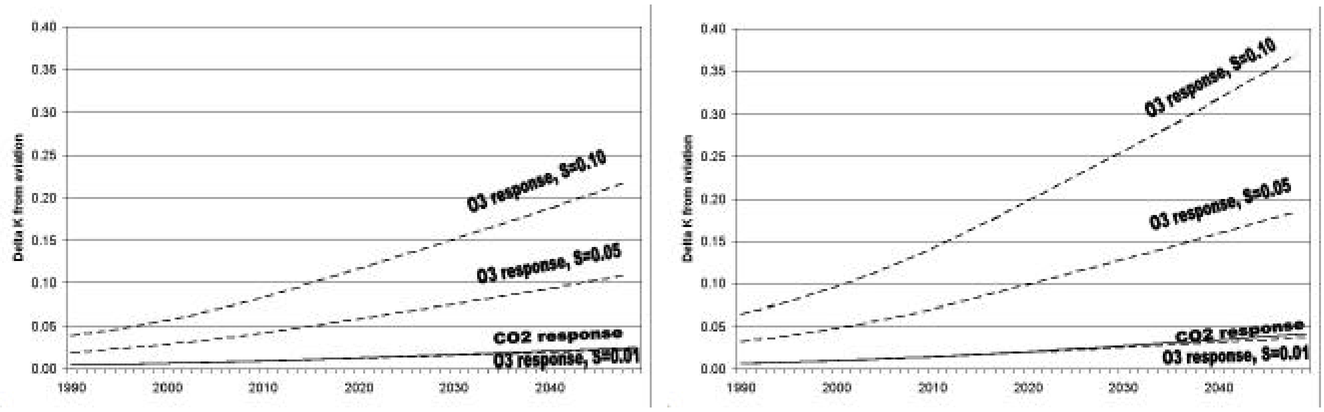

Figure 1. Temperature response from CO2 and O3, 'ECHAM3/LSG' (S&S) model mode (left panel) and 'TAR' model mode with parameter updates (right panel). Scenario F1a and different values of the parameter S form S&S have been considered.

3.2 *Climate responses to technology scenarios*

The three emission scenarios in terms of $EINO_x$ are shown in Fig. 2. Only the effects of NO_x on O_3 were considered in terms of temperature response, which is shown in Fig. 3. This shows that if it is assumed that improved NO_x technology is introduced 10 years earlier than previously assumed in IPCC (1999), and fleet $EINO_x$ reduces at the same rate as assumed in Fa2, then by 2050, the increased warming effect from O_3 is reduced by 20% over the Fa1 'base case'.

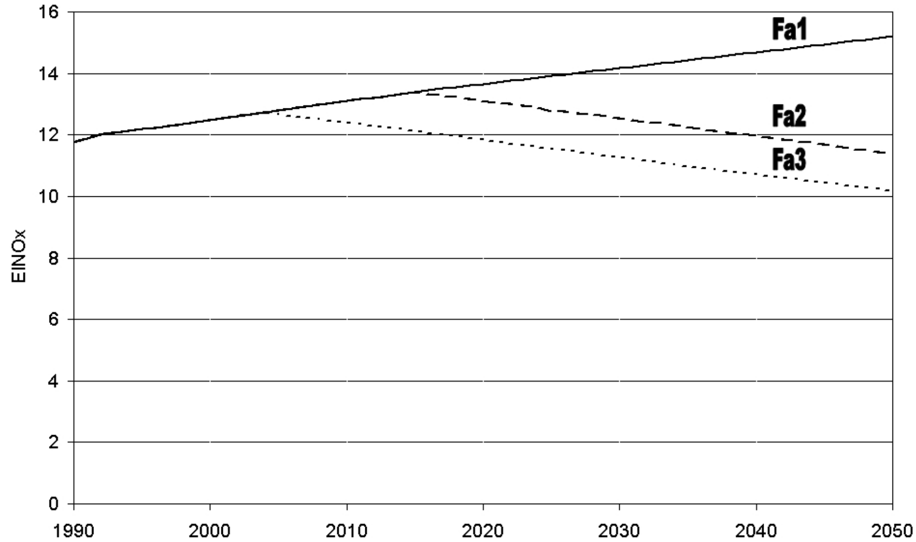

Figure 2. Assumed time evolution of global fleet EINOx, 1990 to 2050.

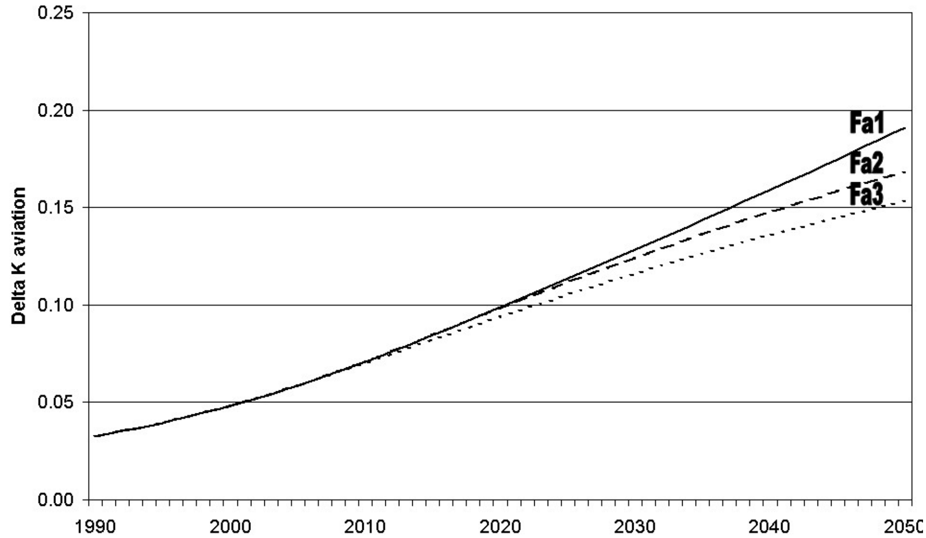

Figure 3. Temperature response from O_3; Fa1, Fa2 and 'Fa3' scenarios (TAR model mode)

3.3 *Uncertainties in aviation growth scenarios*

The 'central' scenario used by the IPCC (1999) was Fa1. Global traffic statistics from ICAO between 1995 and 2000 showed that aviation growth and emissions followed the Fe scenario more closely up. If long-term growth of aviation is unaffected by recent events and the Fe1 scenario prevails, the combined temperature response from CO_2 and O_3 will be approximately 29% greater than Fa1 by 2050, as shown in Fig. 4.

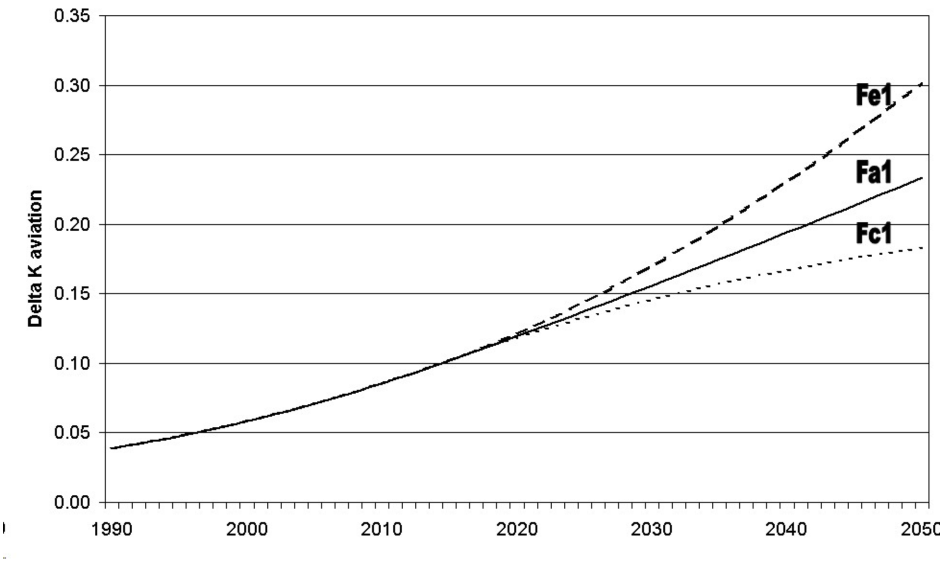

Figure 4. Total temperature response from CO_2 & O_3; Fa1, Fe1 and Fc1 scenarios (TAR model mode)

4 DISCUSSION

The work here provides some updates of the original work of Sausen and Schumann (2000). If a generalized 'TAR' linear response model is formulated, then the impact of CO2 increases substantially (70%), as does the response from O3 (58%). The underlying reason for this is the changed assumption in the temperature response to a doubling of CO2: according to the IPCC TAR (IPCC, 2001), the mean temperature response of 17 models to a doubling of CO2 was 3.8 K. In the TAR model mode, the aviation CO2 impact is a smaller fraction (18%) of the total temperature response from CO2 + O3 by 2050, assuming a best estimate of the equilibrium temperature response to a perturbation of O3.

If aviation growth follows the Fe scenario (based upon IS92e), rather than Fa (IS92a), then the total impacts will be larger than originally calculated by S&S (2000). Opposing this trend is the so-called 'Fa3' scenario formulated here: in this, NO_x impacts on O_3 follow a lower growth rate because of improvements in the NOx technology.

The conclusions on the relative impacts of O_3 to CO_2 were shown in the previous work of S&S (2000) to be highly dependent on the equilibrium response temperature of aviation-induced O_3 (taken from Ponater *et al*., 1999). This is a parameter that is not easily computed as it requires a coupled GCM-CTM simulation. Evidently, more estimates from coupled GCM-CTMs are needed to quantify this response more robustly.

5 CONCLUSIONS

Qualitatively, the results of the model show that more benefits may accrue from targeting NOx reductions than CO2 in terms of climate response – as did the original S&S model. Updated parameters in the model ('TAR mode') do not change this conclusion. This conclusion depends on the equilibrium temperature response for O3 from aircraft – a poorly quantified parameter. Further calculations of this parameter are required.

The CO_2 response in the 'TAR mode' is increased by 70% and the O_3 response by 58%, compared to the 'ECHAM3/LSG mode'; in the TAR mode, CO_2 was 18% of the total temperature response in 2050.

A new emissions scenario based upon industry data shows a reduced temperature increase of 20% from O_3, over the base case Fa1 scenario.

The model could accommodate a parameterization of the CH_4 and other responses to aircraft NO_x emissions to give a fuller overall climate response.

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