Reducing the climate change impacts of aviation by restricting cruise altitudes

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Abstract

Two of the ways in which air travel affects climate are the emission of carbon dioxide and the creation of high-altitude contrails. The latter have been found to potentially play a major role in climate change accounting for the largest impact from the aviation sector. One possible strategy for reducing the impact of air travel on climate change is to significantly reduce the formation of contrails. This can be achieved by limiting the cruise altitude of aircraft, although the benefits would be dependent upon seasonal effects. If implemented, this sort of policy could severely constrain air space capacity, especially in parts of Europe. In addition, carbon emissions would likely be higher due to less efficient aircraft operation at lower cruise altitudes, which would offset some of the benefits of eliminating contrail formation.

This paper describes an analysis of these trade-offs using the RAMS air space simulation model as applied to European airspace. This model simulates the flight paths and altitudes of each aircraft and is here used to calculate emissions of carbon dioxide and changes in the journey time. For a 1-day Western European traffic sample, calculations suggest annual mean CO$_2$ emissions would be less than 4% higher if cruise altitudes were restricted to prevent contrail formation. The change in journey time depended on aircraft type and route, but average changes remained less than 1 minute. Our analysis demonstrates that altitude restrictions on commercial aircraft could be an effective means of reducing climate change impacts, though it will be necessary to mitigate the increased controller workload conflicts that this will generate.
1. Introduction

Aviation has the potential to influence the global climate through diverse mechanisms. The total annual fuel burned by aircraft contributes a small but significant proportion of global anthropogenic carbon dioxide (CO$_2$) emissions (2% in 1992, (IPCC 1999)), with this proportion set to increase with the projected rise in demand for air travel. Additionally, the fuel products emitted at cruise altitudes enter directly into an atmospheric region that is highly sensitive. While this is not a significant factor for CO$_2$, which has a long lifetime and as such is thoroughly mixed throughout the atmosphere, for species such as nitrogen oxides (NO$_x$) emissions at altitude can have a much greater impact on ozone, and in turn on the atmospheric radiation budget, than those at the surface. A third mechanism for the influence of aviation on climate is through the production of contrails. These linear ice clouds formed in the wake of the aircraft can be persistent, and have been shown to spread to form extended cirrus cloud cover (Minnis et al. 1998). Contrails cover 0.1% of the earth’s surface, making a significant contribution to the global high cloud coverage. In regions with a high number of air traffic movements and with atmospheric conditions conducive to contrail formation, the coverage fraction can be much higher.

Clouds affect the atmosphere near the surface in two opposing ways: by reducing the amount of earth-emitted radiation escaping to space, and by increasing the amount of solar radiation reflected. For contrails, and other high cloud, the effect is larger for the outgoing terrestrial radiation, resulting in a warming at the surface. As a result, contrails have the potential to influence climate on a global or regional scale.
The magnitudes of the impacts of these mechanisms have been considered using the concept of radiative forcing. This is a measure of the change in the energy balance at the earth’s surface attributable to each process. The Intergovernmental Panel on Climate Change (IPCC) special report on aviation (IPCC 1999) identified that the largest contribution to the total radiative forcing due to aircraft may be that of contrails, with a value in the range 0.007 to 0.06 Watts per square metre ($\text{Wm}^{-2}$). The best estimate of 0.02 Wm$^{-2}$ is similar in magnitude to the positive (warming) forcings by CO$_2$. The impacts of a possible increase in cirrus cloud production related to the formation of persistent contrails were found to be potentially significant but poorly understood. This provides a possible additional benefit from a strategy to minimize contrail formation.

For the projected increase in traffic by 2050, best estimates predict a value of 0.1 Wm$^{-2}$ (in the range 0.04 to 0.4), making contrails the largest predicted contributor to the radiative impacts of a subsonic fleet. Radiative forcing is a globally averaged parameter. Unlike CO$_2$, which is thoroughly mixed throughout the atmosphere, contrail impacts are localized in regions of heavy air traffic, primarily in Europe and North America. In these regions, the relative impact of contrails compared to that of aviation-emitted CO$_2$ will be even greater.

Clearly it is desirable to seek to identify possible methods to minimize the climate change impacts of aviation. The large contribution of contrails to the total radiative impact of air traffic indicates that a reduction in this effect could significantly reduce the total aviation impact. Myhre and Stordal (2001) suggest that shifting the peak traffic periods towards sunrise and sunset could reduce the contrail impact. At these times, the amount of solar radiation blocked by the contrails is higher and acts to cancel the warming effect of the trapped earth-emitted radiation. An alternative method would be to reduce contrail production by restricting cruise altitudes. Sausen et al. (1998) found that changes in the cruise altitude of aircraft could significantly
impact on the contrail cover fraction. While this method could effectively eliminate the contrail contribution, the necessary constraints on cruise altitudes would prevent some aircraft from operating at their maximum speed and efficiency. As a result, the implications for total fuel burn, and hence the radiative impact of increased CO$_2$, must be considered.

Factors contributing to contrail production and persistence are discussed in Section 2. In Section 3, the regional and seasonal variations in atmospheric conditions conducive to contrail production are identified and used to determine a seasonal cycle in possible altitude restrictions to be applied to European airspace in order to minimise contrail production. Section 4 describes a case study, using the RAMS simulation model, which quantifies the impact on fuel burn and journey time of imposing these altitude restrictions on a 24-hour sample of air traffic for the 5 States area (i.e. the Benelux countries, Northeast France, Germany and Maastricht Upper Area Control Centre). The final section discusses future research and policy implications of this study.

2. Contrail Production

In the wake of an aircraft, the warm, moist engine exhaust gas expands, mixing with colder and drier ambient air. If, at some point in this mixing process, the amount of water in the air reaches saturation, condensation will occur and water droplets will be formed. The water droplets will rapidly freeze to form ice crystals. If the amount of ambient water vapour is sufficient, the rate of condensation onto the ice is faster than that of evaporation, and these ice crystals will grow to form persistent visible contrails (see Schumann 1996 for a review). While short-lived contrails may be of interest for military operations, where such a visible indicator of aircraft position could compromise security, for climate studies it is these persistent contrails that are of interest.
The production of a contrail by a particular aircraft is dependent on characteristics of the fuel and engine performance and on the ambient atmospheric conditions. The warmest possible temperature at which a given aircraft will produce a contrail can be calculated using the Smidt/Appleman relation:

\[
\frac{d}{dT} \varepsilon_{\text{sat}}(T) = \frac{E_{\text{H}_2\text{O}}}{Q(1-\eta)} \frac{c_p}{\varepsilon} p
\]  

Here, the left hand term is the rate of change of the saturation vapour pressure of ice with respect to temperature evaluated at the threshold temperature \( T \). The right hand expression describes the water vapour pressure and temperature of the expanding exhaust gas. The first term is an aircraft-specific constant (a function of the emitted heat \( Q \) and water vapour \( E_{\text{H}_2\text{O}} \) and the engine propulsive efficiency \( \eta \)). \( \varepsilon \) is the ratio of the molar masses of dry air and water vapour, \( p \) is the atmospheric pressure and \( c_p \) is the specific heat capacity of air at constant pressure.

Typically the threshold temperature at which this equation is satisfied is in the region of -40°C near to cruise altitudes. This threshold temperature increases with atmospheric relative humidity\(^1\), so in more moist regions contrails will form at warmer temperatures. It decreases with

\(^1\) Relative humidity is a measure of the atmospheric water vapour. It is defined as the ratio of water vapour pressure to the saturation water vapour pressure at the same temperature. It can be understood as the ratio of the rate of condensation to the rate of evaporation, so for relative humidity values of less than 100%, evaporation will occur faster than condensation and a water droplet will not form.
altitude, being around 10°C warmer at the surface than at 8km (Schumann 1996). However, the atmospheric temperature decreases with altitude much more rapidly, resulting in the existence of a contrail production layer coinciding with the current preferred cruise altitudes for many aircraft. Below this layer, ambient temperatures are too warm; at the higher end of this layer they are sufficiently cold for contrails to be formed even in very dry conditions. The possible implications of increasing cruise altitudes to fly above the contrail production layer in the warmer lower stratosphere are beyond the scope of this paper.  

3. Potential Contrail fraction

Calculations of the potential fractional contrail cover have been 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. It is calculated from the mean atmospheric temperature and relative humidity over that area and indicates the fraction in which aircraft would produce contrails. This tool allows the average contrail production to be predicted over large areas where the precise atmospheric conditions for individual flight routes are not known.

The NCEP/DOE AMIP-II Reanalysis (NCEP-II) dataset is a global analysis of atmospheric fields produced by assimilating land surface, ship, aircraft, satellite and other data. It is a modified

2 The total radiative forcing from a supersonic jet cruising at stratospheric altitudes has been estimated to be 5 times that due to a subsonic jet (IPCC 1999). The benefits of removal of the contrail effect are outweighed by the radiative impact of accumulated water vapour in the lower stratosphere.

3 Atmospheric Model Intercomparison Project (AMIP) carried out in collaboration between the United States National Centers for Environmental Prediction (NCEP) and the Department of Energy (DOE).
version of the widely used NCEP/NCAR\textsuperscript{4} Reanalysis (Kalnay 1996), produced with the goal of correcting errors and updating the parameterisations of the physical processes. NCEP-II monthly mean temperature and relative humidity data for 2000 have been used to calculate maps of potential contrail cover fraction for each month on a range of atmospheric pressure levels spanning the range of flight cruise altitudes. Calculations were conducted using the method described by Sausen et al. (1998). Initially, maps of fractional cirrus cloud coverage were determined, using the parameterisation:

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

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 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 (1) (Sausen et al.1998).

Figure 1 shows maps of the European potential contrail fraction for January, April, July and October 2000 at 250mb (corresponding to an altitude in the region of 33000ft (10km)). A clear seasonal cycle in potential contrail fraction can be seen, with the fraction being significantly higher in January than in July for all locations. This arises as a result of the colder winter

\textsuperscript{4} Collaborative project between NCEP and the National Center for Atmospheric Research (NCAR).
temperatures, which increase the likelihood of the ambient temperature falling below the threshold for contrail production. It can be seen that even in summer, the potential contrail fraction remains above 5% over much of Europe, particularly the 5 states area where the density of air traffic is particularly high. At a pressure level of 300mb (26000-29000ft (8-9km), shown in Figure 2) the seasonal cycle is even stronger. In October, the 5% level is reached only in Northern Europe, while in July the potential contrail cover never reaches this value.

These seasonal variations in the potential contrail cover have implications for contrail avoidance strategies. Any constraint of flight operations to minimise contrail production should incorporate this seasonal variability to ensure the maximum possible efficiency of operation. Here, in order to determine the flight levels appropriate for such a strategy to be applied over Europe, the following procedure was adopted. First, the NCEP-II temperature and relative humidity values were interpolated onto standard flight levels. In the absence of high vertical resolution measurements of relative humidity, this interpolation technique allowed maps of potential contrail cover fraction for each standard flight level (as defined by the International Civil Aviation Organisation (ICAO)) to be generated. These maps were then used in order to identify, for each grid point, the lowest flight-level at which the potential contrail fraction exceeded a threshold of 5%. In order to define a flight strategy that minimised the likelihood of contrail production, the minimum flight level returned for the grid-points in the 5 states area was used to determine a flight ceiling value for each month. The maximum permitted flight level was then determined to be the flight level below that ceiling. The seasonal cycle in the calculated maximum permitted flight levels for the 5 states area is shown in Figure 3.
4. Case study – 5 states area

4.1 The RAMS simulation model

The RAMS Air Traffic Control Simulator Tool can be used to evaluate the impacts on flight profiles and on controller workload of changes in air traffic procedures. It is a fast time simulator designed for analysis of airspace and air traffic management procedures. For the region to be simulated, data describing the location of sector boundaries, airports and navigation aids (navaids) must be specified. The air traffic control sectors may be specified in four dimensions, allowing variations in the sectorisation over time to be incorporated. Routes are defined according to the sequence of navaids to be used. An air traffic sample, with specified departure and destination airports and simulation entry times, can then be analysed. The model simulates the four dimensional profile of each flight and may be used to quantify the associated air traffic control workload triggered at discrete times in the flight history. As a detailed flight profile is obtained, describing the operation of the aircraft at each of these points throughout the flight, the fuel burn amount for each element of the journey can be calculated. This allows evaluation of the emitted CO$_2$.

Simulations were conducted using traffic, route network and sector data as described in Eurocontrol Experimental Centre (EEC) Report 361 (2001). A 24-hour traffic sample for Friday 12th September 1997 was used, with over 9000 flights. The simulation area, shown in Figure 4, covers a region extending east-west from Berlin, Prague and Vienna to London and Paris, and north-south from Copenhagen and Malmo to Lyon and Milan.

To permit calculation of the total fuel burn for this traffic sample, fuel burn rates from the performance tables of the EEC Base of Aircraft Data (BADA) Revision 3.3 (EEC Note 18/00
2000) were incorporated. Flight speed and rate of climb/descent were also defined according to the BADA performance tables. The dataset has thorough coverage, describing 71 aircraft types directly and a further 115 by equivalence to a directly specified type. Each aircraft in the traffic sample was allocated to one of these 71 performance groups. In the few instances where the aircraft type specified in the traffic sample could not be directly related to one of the 186 types supported by BADA, the aircraft was substituted with an aircraft type with similar operating characteristics (size, range, optimum cruise speed and altitude).

Six simulations were conducted; a control run with no imposed altitude restrictions was followed by 5 runs with maximum permitted flight levels (in 100s feet) constrained to 310, 290, 260, 250 and 240 in order to eliminate contrail formation, as previously discussed. These altitude restrictions were imposed by constraining the flight entry, cruise and exit levels for each element in the traffic sample and by removing higher altitudes from the list of permitted flight levels.

### 4.2 Fuel burn

The increase in total fuel burn over the 24-hour simulation for each of the altitude restrictions imposed (compared with that for the control simulation) is shown in Table 1. The magnitude of the increase in fuel burn increases with the severity of the altitude restriction as more aircraft are forced to fly at an altitude lower than that for optimum performance, and the difference between optimum and enforced cruise altitude becomes larger. For the least restrictive scenario, corresponding to the NCEP-II atmospheric conditions for June-September 2000, there is a 1.6% increase in fuel burn. For the most restrictive (February) scenario, the increase is 7.2%. Taking these values for the 24-hour simulations and weighting according to the number of months for which each altitude restriction would apply, as shown in Figure 3, a value for the annual mean
increase in fuel can be determined. For the traffic sample used here, the flight restrictions applied would result in an increase in total annual fuel burn (and hence in emitted CO\(_2\)) of 3.9%. This increase is clearly a small increase given the environmental benefit of contrail elimination.

### 4.3 Journey time

Restrictions on the permitted cruise altitude will alter the flight duration. For a flight with a lower cruise altitude, the time spent in climb and descent modes will be reduced and the distance covered in the cruise mode increased. The speed in each mode and for each aircraft type varies with altitude. As a result, the total journey time may be increased or decreased when altitude restrictions are imposed, depending on the performance characteristics of the aircraft and on the distance travelled.

Changes in journey time are important for a number of reasons. The cost to the airline of a measure such as the restriction of cruise altitude will be dependent not only on the increased price of fuel, but also on staffing and other costs. There are also potential scheduling problems. This is particularly true for the emerging low cost airlines, which rely on a high utilisation of aircraft with low turn around times on the ground. This leaves little flexibility in the schedule, and a small increase in the operating time for a route could decrease the number of possible daily flights, and therefore reduce revenue. In addition, for short haul flights over land, a significantly increased journey time could act to suppress demand for air travel on a route, particularly where competition from a high-speed rail link exists. While in the long term, such factors could act to further moderate climate impact of emissions through a reduction in the total number of flights, the economic consequences for affected airlines would be considerable.
For long haul flights, it is also possible that an increased journey time could exceed the limits for which a crew could safely work. This would require either the introduction of a stop in the route, or the carrying of two full crews, both costly measures. Some long distance flights may also be unfeasible with current aircraft as less efficient operation at lower altitude may reduce the range. These issues are not relevant to this analysis of European airspace, but would be for a global study.

For the RAMS simulations described, the more restricted the flight altitude, the greater the number of flights diverted from their original flight profile. This is shown in Figure 5. For the most restricted simulation, with a maximum permitted cruise altitude of 24,000ft, just over one third of the 9171 flights have journey times unaffected by the altitude restrictions. For a maximum cruise altitude of 31,000 ft, 60% are unaffected. Of those affected, the number with longer journey times increased sharply with the severity of the altitude restriction. For all simulations, at least 20% of the flights operate faster than in the unrestricted control run. However the gains are small, the average time gain for the faster flights being less than 15 seconds. For the flights with extended journey times, the mean change rose from 10 to 42s as the severity of the altitude restriction increased. The maximum increase in journey time experienced rose from under 12 minutes (31,000ft limit) to over 17 minutes (24,000 ft).

The calculations did indicate a significant dependence on aircraft type. The traffic sample used contained 401 flights by McDonnell Douglas MD80 aircraft\(^5\). These were found to show a

\(^5\) The MD80 is a short to medium range airliner with a typical passenger seating capacity of around 150, depending on configuration. Production of the MD80 series stopped in 1999. Over 1165 were in service in 2000 (Frawley 2001).
disproportionate occurrence of reduced journey time as a result of a reduction in the cruise altitude. For a maximum cruise altitude of 24,000ft, 90% of MD80 flights had a reduced journey time, compared to 21% for the whole traffic sample. For the less severe 31,000ft maximum, almost half of the MD80 flights were faster. However, it should be also noted that two MD80 flights showed the largest increases in journey time for this simulation (over 11 minutes), more than double that shown for any other aircraft type, confirming that the route characteristics are also significant. Among the aircraft types most affected by increases in journey time in the 24,000 ft simulation were the Boeing 757 and 777 and Airbus A310, A320 and A340 aircraft. Of the 406 flights by Boeing 757 aircraft in the traffic sample, 364 experience an increase in journey time. For 160 of these, the increase is more than 5 minutes.

Despite these results for specific aircraft type, the average increase in journey times appears to be small. While any minor change may result in some operational and scheduling changes for airlines, the time differences identified are certainly within the range of day-to-day random variability in flight times, and thus do not appear to be a major obstacle to a policy of this type.

4.4 Controller workload

The European region simulated here has a complex sector configuration and a high volume of traffic. The en-route area contains 10 control centres, incorporating 84 sectors. Additional sectors and control centres are included in the model to ensure correct aircraft profiles into and out of this area. Sector boundaries are defined in 3 dimensions, with up to 4 configurations defined during the 24-hour period. Of the 10 control centres, Maastricht and Karlsruhe are Upper Air Centres (UACs) and control airspace only above altitudes of 24,500ft and 23,500ft.
respectively. The Düsseldorf, Bremen, Frankfurt and Luxemburg centres control only lower level traffic. The Paris and Reims centres contain sectors over the full range of flight levels throughout the day. The remaining centres (Amsterdam and the Computer Assisted National ATC Centre – Belgium (CANAC)) include sectors above 24,500ft only during the morning peak period from 06.00-10.00.

In order to allow fast time simulations to be conducted, a generalised controller task base is used for all sectors. This task base specifies the details of the air traffic conditions requiring an action by the controller (for example, an aircraft entering or leaving the controller window or a conflict between two aircraft requiring evasive action). Each of the defined tasks has an associated time dedicated to that task by the controller. These allocated task times can be used to obtain an estimate of the controller workload.

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 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%, with 5 of these sectors within the Maastricht Upper Air Centre. 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. This increase in the number of severely loaded sectors occurs as
the number of available flight levels is reduced, thereby increasing the traffic density. The total number of sectors is also reduced, as the restriction to 24,000ft removes all traffic from the Maastricht Upper Air Centre and from higher level sectors in other centres.

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 number of recorded conflicts in the en route sectors for each Upper Area Control (UAC) and Area Control Centre (ACC) are shown in Table 2. It can be seen that the total number of conflicts increases with the severity of the altitude restriction applied, with the most restricted simulation having 3.5x the conflicts in the unrestricted control simulation.

By considering the impacts on the ACC/UACs, the effects of the imposed altitude restrictions can be more readily seen. For the Upper Area Control centres (Maastricht and Karlsruhe) and for the Reims control centre, the traffic density in the control simulation is high and capacity is limited, as indicated by the controller workload calculations. Restricting the maximum permitted cruise altitudes reduces the number of available flight levels and so increases the traffic density. The number of conflicts increases with the severity of the restriction applied, except in the most restricted case as traffic is largely constrained within the lower sectors. As a consequence, in
this case there is a significant impact in the Amsterdam, Bremen, Düsseldorf, Frankfurt and Paris centres. It should be noted that even in the least restricted case, conflicts in the UACs more than double. This may be mitigated by the recent imposition of the Reduced Vertical Separation Minimum (RVSM) in European airspace as this introduces an extra available flight level at 30,000ft. However, as RVSM increases the number of flight levels only above 29,000ft there would be no increase in capacity for maximum cruise altitudes below that level.

These results indicate that controller workload capacity could represent a significant constraint for a policy to reduce maximum cruise altitudes, and that mitigation of the impacts would be required.

5. Discussion

The simulations described here have allowed the evaluation of the climate impacts of a strategy to avoid the production of contrails by restricting cruise altitude. It was found that, for the region considered, the imposition of such a strategy would lead to an increase in emitted CO$_2$ of 3.9%.

Considering the radiative forcing as discussed in section 1, the calculations presented here suggest a clear net benefit to the climate. The magnitude of the contrail radiative forcing is comparable with that for CO$_2$. As a result any increase in aviation CO$_2$ emission by less than 100%, occurring concurrently with a near total elimination of contrail production, would result in a reduced total radiative forcing by aviation. However, considering radiative forcing alone excludes the effect of the atmospheric lifetime. A persistent contrail has a lifetime of several hours, while the lifetime of CO$_2$ is many decades. Consequently, the cumulative impact of an increase in annual emissions must be considered. The initial impact of a 3.9% fuel burn
increase on CO₂ radiative forcing by aviation would be less than 3.9% as the current forcing includes the impact of all historic aviation flight. That said, this trade-off effect between the impact of reduced contrail and that of increased CO₂ emission must be considered with caution. Radiative impacts of contrails are localised, while CO₂ emissions affect the global climate.

The results of this case study predict an annual fuel burn change only for the traffic mix and atmospheric conditions of the 5 states region in Europe. Other regions would be expected to have a different seasonal cycle of maximum permitted cruise altitudes dependent on the local atmospheric conditions. The fraction of flights affected by those altitude restrictions would be dependent on the nature of the traffic mix. However, in order to entirely counteract the radiative forcing reduction brought by the elimination of the contrail forcing, the global mean fuel burn would need to at least double in response to the imposed restrictions.

This study has investigated the impact of restricting cruise altitude on fuel burn for the fleet operating in Europe in September 1997. No attempt has been made to change the aircraft type allocated to a given route. This suggests an over-estimated increase in fuel burn. In the long term, the commercial benefits of efficiency would encourage airlines to acquire new aircraft to optimise performance at the lower cruise altitudes imposed. In the shorter term, it is anticipated that airlines with mixed fleets may reconsider the allocation of aircraft to routes to optimise operations. In addition, increases in the efficiency of aircraft, as technological advances are incorporated into the fleet, would be expected to reduce the amount of CO₂ emitted per flight. At the same time, increased efficiency would be associated with an increase in the threshold
temperature for contrail formation\textsuperscript{6}, resulting in contrail formation at lower altitudes. In a contrail avoidance scenario, this would enforce further restrictions on the cruise altitude. The resulting feedback on CO\textsubscript{2} would need to be carefully evaluated.

The flight time analysis for the traffic sample and region considered indicates that the consequences for journey time increase with the severity of the altitude restrictions imposed, but that the mean change in journey time remains much less than one minute. A minority of flights experience larger increases, which could precipitate changes in scheduling. The journey time impact was aircraft and route dependent, and as with fuel burn increases could potentially be mitigated by reallocation of aircraft to different routes. It must be remembered that these flight times correspond only to the journey within the simulated region. Not all of the times calculated will correspond to flights taking off and landing within the simulation area, and some correspond to flights only at cruise. In particular, the impact on complete long haul journey times has not been assessed, and may be much greater than the estimates presented here.

The increase in the number of conflicts associated with the imposition of cruise altitude restrictions suggests that airspace capacity presents a likely constraint to such a policy to reduce the aviation impact on climate. Reconfiguration of the airspace may be required for the safe implementation of altitude restrictions. This could include changes in the vertical sector

\textsuperscript{6}As a higher proportion of the chemical energy of the fuel is used to propel the aircraft, less goes to heat the exhaust gas. This results in cooler exhaust temperatures for the same rate of water vapour emission, and so in a higher relative humidity. The contrail production threshold temperature increases by about 1.4K for a 10% increase in efficiency (Schumann 1996). This refers to engine propulsion efficiency only. Improvements in airframe design would reduce fuel burn without impacting on contrail production.
boundaries throughout the year in order to maintain acceptable traffic density. Further benefits could be obtained by applying a range of altitude restrictions according to aircraft type. This would take into account the small dependence of the contrail formation threshold on engine operating characteristics, but could also be used to optimise efficient operation. Aircraft types with the largest fuel burn and time penalties due to altitude restrictions could be allocated flight levels at the higher end of the permitted range to minimise the impact. In addition, aircraft currently cruising at the maximum altitude to be imposed could be moved to a lower level to alleviate capacity constraints. These measures would improve the vertical distribution of traffic and should act to reduce the number of conflict events. Further capacity improvements would be expected from proposed ‘free-flight’ technologies, which would allow greater autonomy in the selection of routes. By eliminating the current necessity to follow a defined sequence of fixed navigation aids, this would enable more direct routing to be adopted. The resulting improvement in the distribution of traffic could reduce the number of potential conflict events.

The results presented here indicate that a strategy to avoid the production of contrails by restricting cruise altitude could provide a net benefit to climate, despite the associated increase in CO$_2$ emission. The analysis suggests that the implications for controller workload present the most likely operational obstacles to such a scheme and that reconfiguration of airspace would be required to mitigate the impacts.

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Acknowledgements

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Figures

Figure 1 Potential contrail cover at an atmospheric pressure of 250mb, which corresponds to an altitude of around 33000ft (10km). It is a measure of the maximum possible contrail coverage given the ambient atmospheric conditions and is calculated using temperature and relative humidity data from NCEP-II data for 2000.

Figure 2 As Figure 1, but at 300mb, which corresponds to an altitude of 26000-29000ft (8-9km).

Figure 3 The annual cycle in maximum permitted flight levels used for the RAMS simulations. Calculated using a threshold potential contrail fraction of 5%, determined using NCEP-II temperature and relative humidity data for 2000 interpolated onto standard flight levels.

Figure 4 Coverage of the RAMS 5states simulation. Air traffic control sector boundaries are marked.

Figure 5 Proportion of flights in each simulation whose journey times are affected by the altitude restrictions imposed.
<table>
<thead>
<tr>
<th>Maximum flight level (in 100s of feet)</th>
<th>Months</th>
<th>% Change in fuel burn (compared to control simulation)</th>
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<tr>
<td>240</td>
<td>February</td>
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<td>January, March, November, December</td>
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<td>June, July, August, September</td>
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<td><strong>AVERAGE OVER YEAR</strong></td>
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Table 1
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<th>ACC/UAC</th>
<th>Maximum permitted cruise altitude (100s feet)</th>
<th>Control simulation</th>
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<td></td>
<td>240  250  260  290  310</td>
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Table 2 Number of conflicts