VARIABILITY OF CONTRAIL FORMATION CONDITIONS AND THE IMPLICATIONS FOR POLICIES TO REDUCE THE CLIMATE IMPACTS OF AVIATION

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Abstract

The contribution of air travel to climate change is significant and growing, but emissions and their effects are not yet regulated. One of the major impacts on climate from the aviation sector is the production of contrails (vapour trails) in the atmosphere and their influence on cirrus cloud formation. Potentially, reducing cruise altitude represents one option for controlling the growing climate impact of aviation. In general, this would reduce contrail and cirrus cloud formation but there are associated penalties, including an increase in the rate of fuel consumption and hence in the rate of carbon dioxide emission. Constraining cruise altitudes also raises operational issues, including increases in airspace congestion and in journey time.

Atmospheric variability can change the amount of contrail and contrail-cirrus, so contrails may sometimes be more likely to form at lower altitudes. In these cases, reducing cruise altitude could increase rather than reduce the contrail amount.

This paper describes an approach to optimise the balance between the benefits of contrail reduction and the penalties incurred for altitude restriction. The calculations use an air traffic sample for western Europe, with NCEP-II reanalysis data for atmospheric temperature and humidity. A maximum cruise altitude is selected for each six-hour period, according to atmospheric conditions. This altitude provides the greatest reduction in contrail for the lowest increase in carbon dioxide emission. This avoids the contrail and carbon dioxide increases associated with ineffective or counter-productive altitude restrictions. Calculated contrail reductions are presented, along with the associated increases in carbon dioxide. These values compare favourably with previous policy designs based on altitude restrictions fixed on a monthly basis. In addition, potential operational issues associated with a varying altitude restriction policy are discussed.

Introduction

The consumption of aviation fuel continues to increase, despite efficiency gains from improvements in engine and airframe design. Continued growth in air travel means aviation fuel accounts for a growing share of global fossil fuel use and of anthropogenic CO_2 emissions. These emissions represent only one of the mechanisms through which aviation can influence the global climate.

At high altitudes, in appropriate atmospheric conditions, the expanding aircraft exhaust triggers the formation of a contrail, which may persist for several hours. These contrails can spread to form extensive cirrus clouds. During the near-complete shutdown of air traffic over the United States following September 11th 2001, the contrails from just 6 military aircraft spread to form cirrus cloud coverage over 20,000km^2 [1]. The combination of linear contrail and long lasting contrail spreading to form cirrus cloud are considered to make a substantial contribution to the radiative forcing of climate by aviation. The Intergovernmental Panel on Climate Change (IPCC) special report on aviation estimated the radiative impact of linear contrail to be similar in magnitude to that of CO_2 emitted by aircraft, and identified considerable uncertainties in assessing the impact of aviation-induced cirrus clouds [2]. Recent research has improved the understanding of the radiative impacts of both contrail and cirrus cloud, identifying a smaller contribution from linear contrail than estimated by IPCC, but a larger impact from aged contrail spreading to form extensive cirrus cloud. One study suggests this to be at least 10 times that of the CO_2 from aviation [3].

In addition to CO_2 emissions and the formation of contrail, the formation of NO_x in the combustion process also has significant radiative impacts by increasing ozone and reducing methane. Other minor contributors include increases in sulphate aerosol. The total impact of aviation on the global climate arises from the net combination of these impacts, taking into account differences in their spatial and temporal characteristics.

This total climate impact of aviation is currently unregulated. The Kyoto Protocol includes carbon dioxide emissions from domestic aviation in national targets. However, other impacts specific to aviation are not included in the protocol and will remain unregulated in the absence of additional agreements. These include high-altitude emissions of NO_x and the formation of contrails and cirrus clouds. In addition, policies to restrict climate impacts of international aviation have not yet been agreed. Proposals have been explored at the European and global level, many focussing on policies to reduce carbon dioxide emissions.

Cruise altitude changes have been explored as a policy option to reduce the climate impact of aviation by preventing or reducing the formation of contrails [4, 5] or by reducing the impact on ozone of aviation NOx emissions [6]. Reductions in cruise altitude have also been identified as a way to reduce the climate impact of stratospheric water vapour emissions from a potential hydrogen fuelled aircraft fleet [7]. However, reducing cruise altitude raises a number of issues. The first is that it forces aircraft to fly through denser air, below their most efficient altitudes. This increases the rate at which fuel is burned, increasing the amount of carbon dioxide emitted as well as airline costs. In addition, this increased fuel requirement either increases the take-off weight of the aircraft or reduces the pay-load which can be carried, and changes in the aircraft speed raise additional operational issues associated with journey time. Air space congestion is a further constraint on altitude restriction policies. This is particularly relevant in regions where the density of air traffic is already high.

Previous work by the authors [4] identified a policy design for altitude restrictions based on monthly mean atmospheric conditions for the European 5 states region and calculated the associated penalties for CO_2 emission, journey time and airspace congestion. This paper adds to the authors' previous research in this area by presenting an analysis of the short-term variability in the atmospheric conditions conducive to contrail formation in the same region and developing a revised altitude restriction policy. The carbon dioxide penalties for altitude restriction previously presented [4] were based on fixed altitude restrictions applied for each month with the severity of restriction calculated from one year of monthly mean temperature and humidity data. This paper uses 5 years of 6 hourly data and considers contrail formation for January, April, July and October. Using instantaneous, rather than monthly averaged, temperature and humidity data improves the representation of contrail formation conditions.

In the analysis presented here, the altitude restrictions are not set based on monthly mean atmospheric conditions. Instead, the altitude restriction is allowed to vary every six hours. This leads to a reduction in the potential increase in fuel burn and consequent carbon emissions from the altitude restrictions. In a further improvement to the design criteria for the altitude restriction policy, the selection of cruise altitude includes traffic distribution data to target restrictions more effectively. The approach adopted for contrail calculations is described in more detail in section 2, followed by the development of the altitude restriction policy and a discussion of operational implications.

Estimating Variability in Contrail Coverage

A measure of contrail sensitivity is developed using a parameterisation of the maximum potential contrail coverage combined with air traffic density data. This measure is based on a 1-day sample of air traffic in the European 5 states region and is based on previous methods for calculating potential contrail fraction (Sausen et al., 1998) and actual recorded movements of aircraft within 3-dimensional grid cells.

This method has a few key changes from previous techniques. First, the use of detailed flight profile data allows distance travelled, rather than fuel burned, to be used as the measure of air traffic density. In this way, aircraft burning more fuel per kilometre are not over-represented in the distribution of calculated contrail coverage. A second distinction is that no attempt is made to scale the calculated measure of contrail coverage to observed contrail. Previous studies have calculated this scaling factor using satellite observations of contrail coverage over Europe [8] with calculated contrail coverage from atmospheric data and air traffic density in order to calculate global fractional contrail coverage [9]. The calculated contrail sensitivity used here is simply a measure of the distance of linear contrail formed per km of flight in the traffic sample.

Calculations of contrail coverage from air traffic density and gridded atmospheric data require calculations of the potential contrail fraction. This is determined from a parameterisation to reflect the sub-grid scale variability of relative humidity and temperature and which describes the fraction of a grid box in which a contrail could form. Here, it is assumed that contrail cover is not saturated within a grid box, so that the contrail amount for a given set of atmospheric conditions is linearly dependent on the amount of air traffic.

A single day of air traffic data is used, with the traffic divided into four 6-hour periods. Cumulative distance travelled by aircraft through each 3-D grid box in each time period is calculated. The grid for the NCEP-II data is used, with a resolution of 2.5° latitude by 2.5° longitude and vertical levels at 400hPa, 300hPa, 250hPa, 200hPa and 150hPa. For each day of atmospheric data analysed, the cumulative distance travelled is multiplied by the potential contrail fraction for each of the four periods. Summing this product over all grid boxes provides an indication of the total amount of contrail for each time step (*CC*), as follows:

$$CC_{t,d} = \sum_{i=1,I}\left(PCF_{i,t,d} \cdot \sum_{n=1,N} x_{n,i,t} \right) \qquad (1)$$

Here, *I* is the total number of grid boxes, $PCF_{i,t,d}$ is the potential contrail fraction calculated for grid box *i*, at time *t* for day *d*, *N* is the number of aircraft in the traffic sample and $x_{n,i,t}$ is the distance travelled by aircraft *n* through grid box *i* during the time *t*. This provides a measure of the total contrail coverage associated with the traffic sample for each day of atmospheric data, which is then divided by total distance travelled to obtain the contrail sensitivity.

This measure of contrail sensitivity must be used with caution. It does not imply that increasing air traffic km in the sample by 50% would produce a 50% increase in contrail; the change in total contrail amount would depend on the distribution of the additional air traffic. The contrail sensitivity is used here to adjust contrail coverage calculated in response to the diurnal cycle in air traffic. Distinction should also be made between the contrail sensitivity used to explore the variability in contrail production and the ratio of contrail reduction to carbon dioxide emission increase, which is used in the design of the altitude restriction policy.

A one day air traffic sample for the European 5 states region is used [4, 10]. Figure 1 shows the air traffic routes in the sample. The distance travelled in each atmospheric data grid box is used as a measure of air traffic density and is obtained using the Reorganised Air traffic control Mathematical Simulator (RAMS)[1]. This is a fast time simulator which allows detailed calculation of aircraft trajectories, taking into account their performance characteristics, which are specified using the Eurocontrol base of aircraft data (BADA) [11].

The RAMS model is an event based simulator and as such describes the position of each aircraft whenever an air traffic control event takes place. For each flight in the simulation, the flight profile is retrieved using the time and position data from this event list. The flight is divided into flight segments, each described by two events. The position and time data for these two events is used to calculate the (great circle) distance travelled and allocate that distance to the appropriate grid box. Where the two events do not fall within the same grid box, the distance is assigned to the grid box of the first event. The distance travelled in one flight segment is typically very much smaller than the size of a grid box, so the impact of this assumption on the calculated distribution of air traffic is small.

This data for the density of the air traffic sample is used in conjunction with potential contrail fractions calculated using temperature and relative humidity data from the NCEP-II reanalysis dataset [12]. Data from January, April, July and October is used in order to identify differences in the variability between seasons. The NCEP-II data used correspond to 5 years of data at 6 hour intervals, covering 2000-2004 for January and April and 1999-2003 for July and October. To relate this to the 24-hour air traffic sample and provide a realistic measure of the distribution of air traffic density throughout the day, distances travelled through each grid box in the 6 hour period following the NCEP model time are used. The sum of the calculated contrail coverage over all grid boxes and all layers is used as a measure of the total contrail coverage arising from the air traffic in each time period, and divided by the sum of the distance travelled in the corresponding time period to obtain the contrail sensitivity.

For each 6-hour block of the traffic sample, 5 years of data for 4 months of the year were obtained. Figure 2 shows a time series of calculated contrail sensitivity for each month (4 records per day), with data for the 5-years displaced along the x-axis. For each month, the horizontal line shows the mean for that calendar month over the 5-year period. This mean value is highest in January and April, with values approximately double that for July. This seasonal cycle in contrail sensitivity is consistent with the greater probability of contrail formation in winter than in summer identified by previous authors through both atmospheric modelling and data analysis [9] and observations using automated

[1] www2.isa-software.com

detection of contrails from Advanced Very High Resolution Radiometer (AVHRR) [13].

For each of the four months considered, there are identifiable periods characterised by high or low contrail sensitivity values maintained over several days, while other periods show higher frequency variability. This has implications for policies designed to reduce contrail formation and for attempts to characterise the full climate impact of different aircraft-route combinations. Because of the variability in the probability of contrail formation along a route, the net climate impact of an aircraft operating along an identical flight trajectory may vary dramatically from day to day.

The mean, standard deviation and range of calculated contrail sensitivity values over the five years of data for each calendar month are shown in Figure 3. Values for each 6-hour time period are indicated separately. As a result, the range (dashed line) and standard deviations (solid line) described correspond only to changes in atmospheric conditions. Contrail sensitivity shows no strong diurnal cycle. Total contrail production is highest for the air traffic samples for the six hours from 6.00 am and from noon, due to the daytime peak in air traffic over the 5 states region.

The day-to-day variability in calculated contrail sensitivity is considerable. For each time period, the maximum contrail sensitivity is approaching double the mean value.

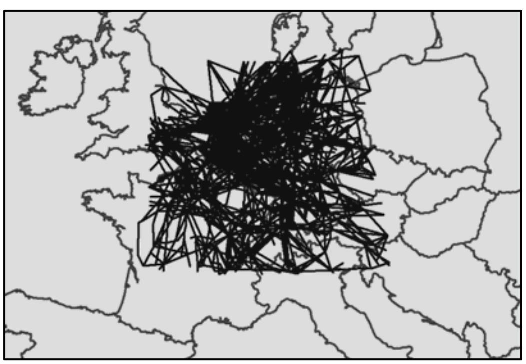

Figure 1. Flight routes included in the air traffic sample for the European 5 states region.

Altitude Restriction Policy

The altitude restriction policy described here applies a single maximum cruise altitude restriction across the region analysed, with that maximum permitted altitude varying every 6 hours according to atmospheric conditions. The altitude restriction to be applied for each time period is selected from 5 options (31,000ft, 29,000ft, 26,000ft, 24,000ft or no restriction), and is chosen to maximise the ratio of reduction in contrail to the additional fuel required.

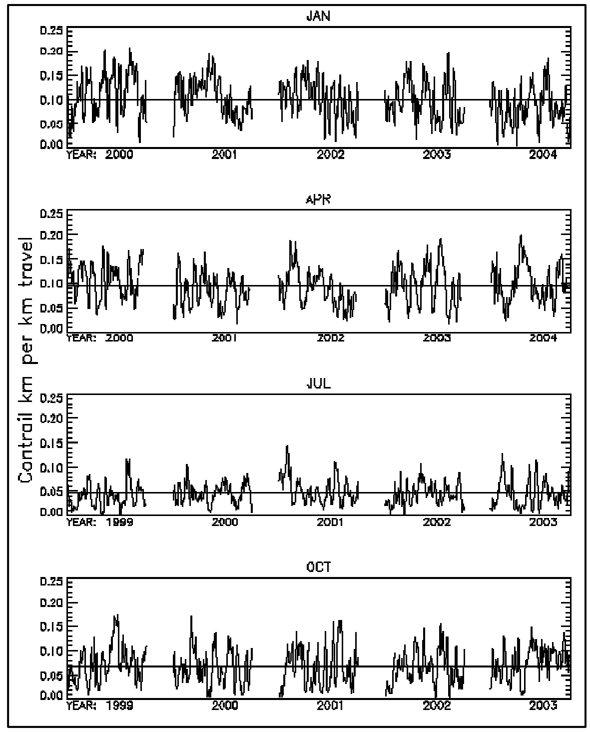

Figure 2. Time series (6-hourly) data of calculated contrail per km of air travel for the fixed one-day air traffic sample, calculated for changing atmospheric conditions. Each time series is one calendar month of data for the month and year indicated. For each figure, the horizontal line shows the mean for the indicated calendar month over the 5 year period.

The method described above was used to calculate the total contrail amount associated with each time period for the control traffic sample. This was then repeated for each of 4 altitude restriction scenarios. The restrictions were applied by imposing a maximum cruise altitude on the traffic sample used for the control run. The origin and destination combinations, the distribution of departures throughout the day, the air traffic control sectors and the type of aircraft for each trip are kept the same. Each of these cruise altitude restrictions is associated with an increase in fuel burn and hence in carbon dioxide emissions as some aircraft are forced to fly less efficiently. The increase in fuel by the total fleet for each of these restricted cruise altitude scenarios has been previously evaluated using the RAMS model in combination with BADA data for aircraft performance and fuel consumption rates [4].

For each of the 4 calendar months considered, Figure 4 shows the mean, standard deviation and range of contrail sensitivity values obtained from 5 years of data. The four times of day are plotted separately, with overlapping symbols indicating little or no diurnal cycle. For both January and April, mean contrail sensitivity is highest for cruise altitudes restricted to 29,000ft and 26,000ft; cruise altitudes must be reduced to 24,000ft to obtain a lower mean contrail sensitivity than produced in the control run where cruise altitudes are not restricted. This contrasts with the results for July and October, which indicate that any of the cruise altitude restrictions reduces mean contrail sensitivity. With the exception of the 24,000ft restriction in July, even where very low values of contrail sensitivity are obtained, the range of values is high, indicating that for some time periods altitude restrictions may increase the probability of contrail formation.

Each of the cruise altitude restrictions applied is associated with an increase in fuel consumed by the air traffic in the sample. These fuel increases were calculated using the RAMS model, with detailed information on aircraft performance data taken from the BADA performance tables [11]. Table 1 shows the fuel increases for each 6-hour period, and for the full day. These fuel increases apply to the total fuel used by all aircraft in the sample. Some aircraft, particularly on shorter routes, already fly at or below the altitude restrictions and so are unaffected.

The variable altitude restriction policy developed here is designed to minimise the penalties that would be incurred while achieving a reduction in contrail by selecting a varying sequence of maximum cruise altitudes. For each time period, the cruise altitude restriction which gives the largest ratio of contrail reduction to carbon dioxide emission increase is selected. For times when each of the altitude restriction scenarios would increase contrail coverage, no restriction is applied. Figure 5 shows the frequency of selection of each cruise altitude.

Figure 6 shows the change in fuel required and contrail produced for the variable and fixed cruise altitude restrictions compared to the control scenario in which cruise altitudes are not restricted. For the fixed altitude restrictions, the contrail change shown for each month is averaged over the 5 years. As the calculations do not include any seasonal signal in air traffic amount or distribution, the effect on fuel burn of applying a fixed altitude restriction is the same for all months and years, depending only on the severity of the restriction imposed. For January and April, fixed monthly altitude restrictions can increase contrail production by up to 30% compared to the unrestricted run, as contrail formation conditions may peak below the normal cruise altitude of some of the aircraft in the sample. Only the most extreme restriction (maximum cruise altitude 24,000ft) offers consistent reductions in the average contrail amount. For July and October, contrail reductions are obtained for each altitude restriction, with the magnitude of the reduction increasing with the severity of the restriction applied.

On the same figure, corresponding changes in contrail and fuel for the variable altitude restrictions are plotted for each month and year. Broadly, the variable policy consistently reduces the amount of contrail predicted by the model by between 65 and 95%. For January and April, the contrail reductions obtained for the variable restrictions approach those associated with a cruise altitude restriction fixed at 24,000ft, but with a smaller increase in the fuel required. For July and October, the contrail reductions are somewhat smaller than those obtained for the most extreme fixed altitude restriction (which virtually eliminates contrail), but compared to the fixed scenarios at 26,000 and 29,000ft the variable restrictions offer improved contrail reduction for similar fuel increases.

In addition to the fuel burn and air traffic congestion penalties associated with imposing lower cruise altitudes, this variable policy would present additional difficulties associated with the transition between restrictions. These issues have not yet been fully explored using the air traffic simulator, but some insight into the distribution of these problems can be gained by considering the number of transitions between cruise altitude restrictions. Table 2 shows the number of transitions for each month and year considered. For January, the maximum cruise altitude imposed changes on average 24.2 times (out of 124 6-hour time periods). April has the most stable conditions, with an average of only 19 transitions. There are 34 and 36.2 for July and October respectively, representing more than one change in cruise altitude restriction per day. This suggests that although the restrictions required are generally less severe for July and October (as shown in Figure 5) implying fewer penalties for airspace congestion, the additional airspace complexity resulting from frequent changes in the restriction could present a significant challenge to the implementation of such a policy. The operational and fuel burn issues associated with the transition between cruise altitude regimes are discussed further in the following section.

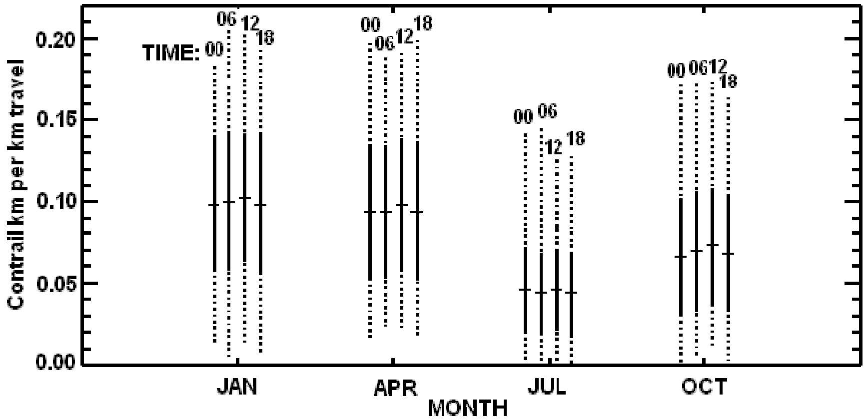

Figure 3. Variability in contrail km per km travel associated with changing atmospheric conditions. For each calendar month analysed, the mean value (+), mean +/- 1 standard deviation (solid line) and the full range of values obtained (dashed line) are shown for four times of day.

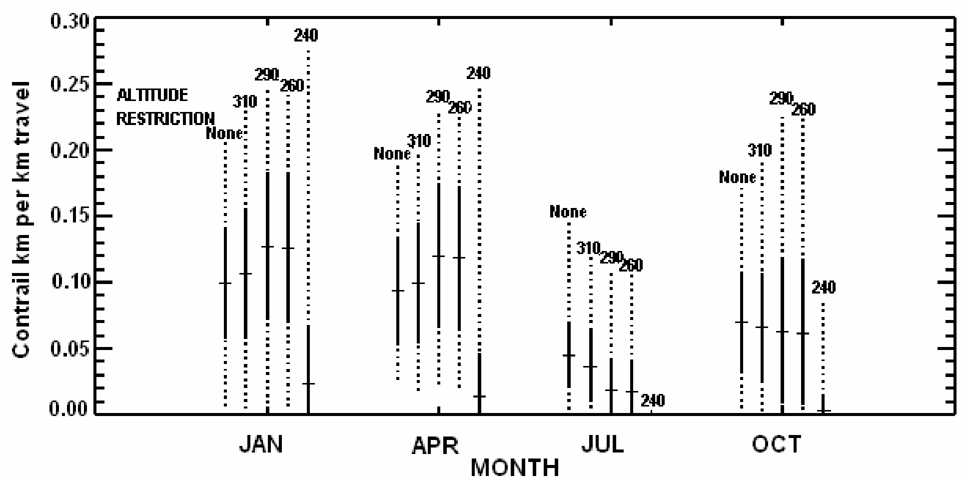

Figure 4. The effect of restricting cruise altitude on calculated contrail sensitivity. For each calendar month analysed, the mean value (+), mean +/- 1 standard deviation (solid line) and the full range of values obtained (dashed line) are shown for the control simulation and 4 altitude restrictions. Values shown relate to 5 years of data and only to the 6-hours from 6.00am.

4. Operational implications of variable altitude restrictions

Applying variable altitude restrictions presents new challenges for the management of air traffic. The calculations described above assume instantaneous changes between the maximum cruise altitude applied. In order to gain some insight into the operational issues associated with variable cruise altitudes, additional RAMS simulations were conducted. To allow a smoother transition between altitude restriction regimes, each aircraft is allocated a maximum cruise altitude according to the time in which it enters the traffic simulation. Two simulations were undertaken. The first, referred to as PM240, applied no altitude restriction to air traffic for the first twelve hours, with aircraft entering the simulation after midday allocated a maximum cruise altitude of 24,000ft. The second simulation (AM240) reversed this, applying a 24,000ft restriction before midday, but not restricting aircraft entering the simulation in the afternoon. The two simulations with changing cruise altitude restriction regimes are compared with two of the simulations described above: the control traffic sample with no altitude restriction applied and the most restricted of the fixed cruise altitudes, with a maximum of 24,000ft imposed for the full day.

The number of conflict events is a simplified measure of the complexity of the air traffic sample. These events occur when aircraft separation conditions are violated; two aircraft are in conflict when each occupies the 3-dimensional protection zone defined around the other. Compared with the unrestricted simulation, the number of conflicts in the whole simulation region increases with the severity of the altitude restriction applied. However, as the definitions of air traffic control sector and centre boundaries are fixed, high-level centres can experience a reduction in conflicts as traffic diverts to lower altitudes. As the two transition scenarios both represent conditions in which the extreme altitude restriction is applied for half a day, assuming instantaneous transition between the two regimes would suggest that the total number of conflicts for each centre over the day would be between that obtained for the control scenario and that for the full day 24,000ft restriction. However, preliminary analysis of the conflict data for these simulations suggests that exceptions may occur. For example, for the Karlsruhe Centre, the AM240 simulation identifies more conflict events in the hour from noon to 1.00pm than either the control scenario or the full day 24,000ft restriction. This suggests that, for this centre at least, the change in altitude restriction can induce additional conflicts. For the same hour in the PM240 simulation, there are fewer conflicts than in either the control scenario or the full day 24,000ft restriction.

The simulations AM240 and PM240 also allow the impact of the assumption of instantaneous transition between maximum cruise altitudes to be tested. As there is a gradual transition between regimes, the impact of the altitude restriction selected will be diluted until air traffic entering the simulation at an earlier time has completed its route, either by reaching its destination airport or by leaving the simulation area. Compared to the control run simulation, in which altitudes are not restricted, the simulation AM240 increases fuel by 4% over the whole day. For the PM240 simulation, the fuel increase is 3.2% of the control run value. Using the breakdown of fuel usage with time for the control and the 24,000ft restriction simulation, it is possible to calculate the total fuel burn that would occur if it were possible for the transition between altitude restriction regimes to take place instantaneously. This requires summing a.m. data from one simulation with p.m. data for the other. Increases of 3.7% and 3.5% for AM240 and PM240 respectively are obtained.

Further calculations are required to evaluate the extent of the assumption of an instantaneous change between restrictions on calculated contrail. These calculations will be limited to the days with atmospheric conditions consistent with this combination of altitude restrictions. Of the 615 days in the policy design presented here (5 years of data for 4 calendar months), 3 follow the altitude restrictions for PM240, while 1 follows AM240. Extending the analysis to other months and years would be likely to yield further dates for comparison. The effects of less extreme and more frequent transitions in altitude should also be considered.

Table 1. The increase in total fuel required for the air traffic sample for each of the 4 altitude restriction scenarios considered, compared to the traffic sample with no altitude restriction applied. Increases are shown for the four 6-hour periods, and for the full traffic sample.

Time of Day	FL310	FL290	FL260	FL240
00:00-05:59	3.25	5.14	8.67	1.12
06:00-11:59	1.44	2.43	4.79	6.49
12:00-17:59	1.42	2.42	4.68	6.63
18:00-23:59	1.44	2.55	5.14	7.09
00:00-23:59	1.67	2.81	5.34	7.28

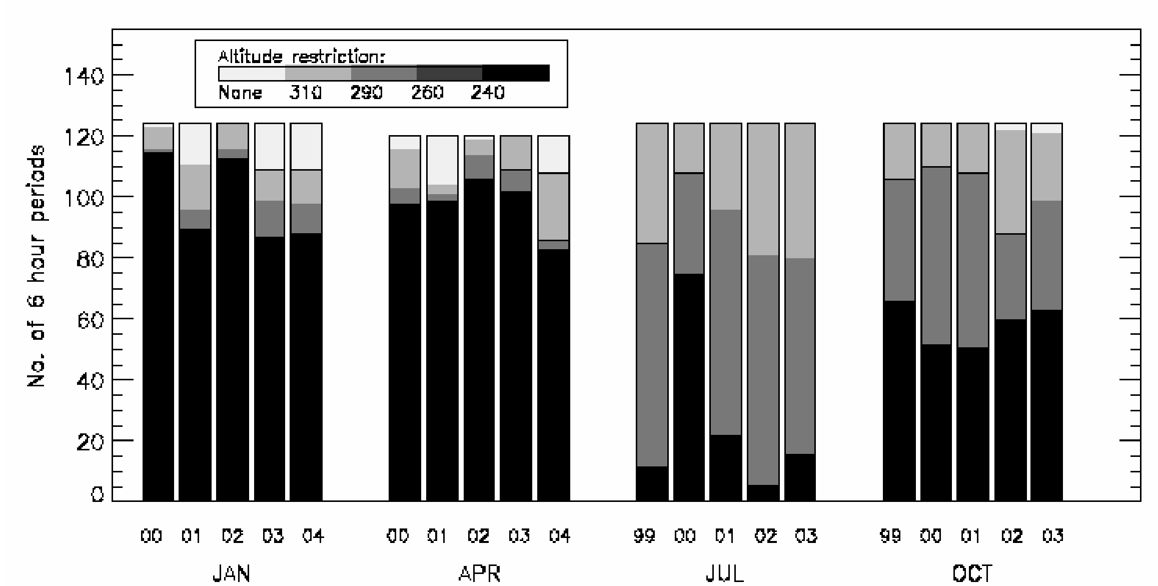

Figure 5. Frequency of selection of altitude restrictions for the combinations of altitude restrictions for each month and year.

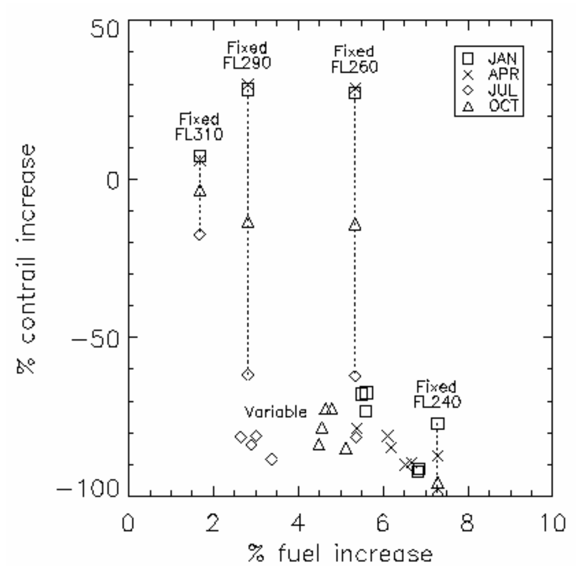

Figure 6. Contrail increase against fuel increase for each of the combinations of altitude restrictions. For the fixed altitude restrictions, the contrail change shown for each month is averaged over the 5 years.

5. Discussion

These results highlight the considerable variability in the production of contrail. This has strong implications for policies to address the impact of aviation on climate. First, while applying a blanket altitude restriction could reduce mean contrail, significant further reductions could be obtained using an adaptive policy, allowing restrictions to be altered when contrail sensitivity at low altitude is unusually high. This presents technical challenges for air traffic management and raises operational issues related to the difficulty to predict precise journey times in advance. A policy optimising the altitude restrictions required could reduce the penalties by ensuring that unnecessary or counter-productive flight restrictions were not imposed. One example of such a policy is presented, and is shown to offer improved contrail reduction with a smaller increase in carbon dioxide than fixed altitude restriction options.

Improving the selection of altitude restrictions could further reduce the penalties incurred. Options to enhance the selection procedure include:

- **Increasing range and resolution.** Including more possible altitude restrictions in the analysis would increase the available options from which to select. The additional flight levels considered could offer improved contrail reduction for a smaller increase in the fuel required.
- **Specifying a threshold for contrail reduction.** For each time period, the current method selects the cruise altitude restriction which provides the best ratio between contrail reduction and increased fuel consumption. The unrestricted cruise altitude option is selected only if each of the altitude restrictions will increase the contrail amount.

In some instances, an altitude restriction may be selected despite providing only a very small contrail reduction. Setting a threshold value for the minimum contrail reduction to be obtained if an altitude restriction is to be applied would prevent the imposition of restrictions whose effect on contrail is minimal.

- **Optimising for longer time periods** The method described here considers each 6-hour period in isolation in order to design a combination of altitude restrictions. Adapting an altitude restriction policy in response to forecast data would require some differences in approach. It would be possible to follow a similar procedure to that outlined above in order to identify the preferred combination of altitude restrictions during a short forecast period. By including likely future conditions in the selection of cruise altitudes, restrictions could be more effectively targeted. However, larger total contrail reductions and reduced CO_2 increases in the longer term could potentially be achieved by including long term analysis of seasonal variability. This could avoid the imposition of altitude restrictions where the predicted contrail coverage throughout the forecast period is already lower than average for the time of year, to ensure that the altitude restrictions are applied effectively and efficiently to achieve substantial reductions in the mean contrail coverage.

Table 2. Number of transitions between flight altitude restrictions.

	99-00	00-01	01-02	02-03	03-04
JAN	10	27	19	30	35
APR	21	21	14	14	25
JUL	37	45	24	35	29
OCT	42	39	43	40	17

Changes in cruise altitude present challenges for the management of air traffic flows, particularly in this variable policy design. More consideration of these implications is required. Some improvements in the management could potentially be obtained by staggering the imposition of the cruise altitude restriction change, for example by applying it only to aircraft entering the control area after the start of the new restriction period. Further changes to the optimised policy design could be made to reduce the disruption to air traffic control caused by a highly varying cruise altitude policy. The policy adaptations described above would reduce disruption by preventing a change in cruise altitude if it is likely to have only minimal impact on total contrail.

The variability in contrail sensitivity also presents difficulties for any scheme involving either tradable permits or penalties/incentives based on net climate impact. This would need to include a measure of actual contrail production attributable to individual air traffic movements if the “polluter pays” principle is to be applied effectively.

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