AIRCRAFT EMISSIONS AND CLIMATE CHANGE: ATMOSPHERIC VARIABILITY AND THE IMPLICATIONS FOR CLIMATE POLICY

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ABSTRACT
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. Contrail coverage is recognised to play a significant role in climate forcing by aviation and new estimates have suggested that the radiative impact of cirrus clouds formed by spreading contrails may be up to 10 times larger than that due to aviation emissions of CO_2 [4]. Contrail formation requires appropriate ambient conditions. As such, atmospheric variability can change the amount of contrail and contrail-cirrus and hence the net radiative impact of a sample of air traffic.
This research takes a new look at the issue of contrail formation, in the context of the wide range of proposed market-based and other measures to address the impact of aviation on climate. The variability in the atmospheric conditions conducive to contrail formation is analysed with a focus on identifying possible unintended climate consequences of policies designed to reduce climate impacts of aviation by restricting cruise altitude. The study considers the key region of Western Europe, where the high density of air traffic and prevailing climate conditions lead to high contrail coverage. Initial results suggest that while fixed or monthly varying altitude restrictions could significantly reduce mean contrail, variability is such that, on a limited number of days, contrail could be increased above that produced by unrestricted air traffic. Incorporating forecasting to predict these days and adapt altitude restrictions accordingly could provide significant further reductions in mean contrail and associated cirrus cloud.

INTRODUCTION
Aviation is a significant and growing contributor to anthropogenic forcing of climate. There is no current regulation to control cruise altitude emissions or the climate impacts of aviation. The Kyoto Protocol, which is yet to be ratified by sufficient partners to come into force, 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.
A range of policy proposals have been explored at the European and global level, many focussing on policies to reduce carbon dioxide emissions. Cruise altitude changes have also been explored as a policy option to reduce the climate impact of aviation by preventing or reducing the formation of contrails [8, 9] or by reducing the production of ozone from aviation NOx emissions. 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].

Previous work [9] 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 presents an analysis of the day to day variability in the atmospheric conditions conducive to contrail formation in same region and discusses the implications of this variability for policies to reduce the climate impact of aviation.

METHODOLOGY

Using a parameterisation of the maximum potential contrail coverage combined with air traffic density data, a measure of contrail sensitivity is obtained for a 1 day sample of air traffic in the European 5 states region. The method for calculating contrail produced follows previous studies [6] with a few key exceptions. Firstly, the use of detailed flight profile data allows distance travelled, rather than fuel burn, 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 [1] with calculated contrail coverage from atmospheric data and air traffic density in order to calculate global fractional contrail coverage [6]. 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, which is determined from a parameterisation to reflect the sub-grid scale variability in 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. For each day of atmospheric data analysed, the cumulative distance travelled is multiplied by the potential contrail fraction for each of the 4 time periods. Summing this product over all grid boxes provides an indication of the total amount of contrail for each time step (CC), as follows:

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

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.

DATA

A one day air traffic sample for the European 5 states region is used [2, 9]. 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) [5].

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 [3]. For this initial analysis, January data is used in order to identify winter variability, when altitude restrictions for significant contrail reduction would need to be most severe. The NCEP-II data used correspond to 5 years (2000-2004) of January data at 6 hour intervals. 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.

RESULTS

Diurnal cycle in contrail production

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, 155 values for the contrail sensitivity were obtained (5 years of January data, each with 31 days). The range of values obtained for each 6hr period is shown in Figure 1 (blue bars). For each range, the diamond symbol indicates the mean of the 155 data records. Contrail sensitivity shows no strong diurnal cycle, with an average linear contrail formation of 8% of the distance travelled. The total distance travelled for the air traffic sample during each time period is indicated in Figure 1, (red asterisks). Due to the day time peak in air traffic over the 5 states region, total contrail production is highest for the air traffic samples for the six hours from 6.00 am and from noon.

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.

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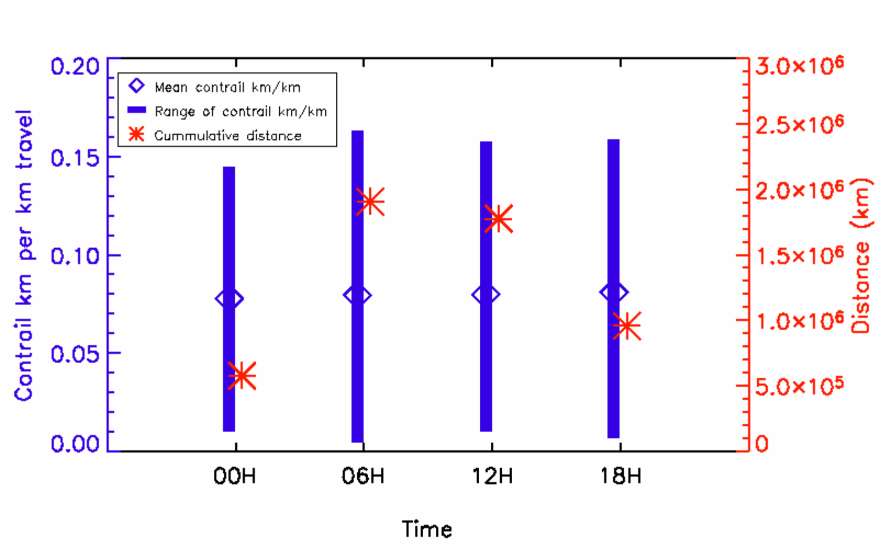

Figure 1 Contrail km per km travelled calculated using one day air traffic sample for Western Europe, split into 4 six hour periods with six hourly NCEP-II January atmospheric data for five years (2000-2004) for the same region. The red asterisk indicates the total distance travelled by air traffic in the sample during the 6 hour time period (right axis).

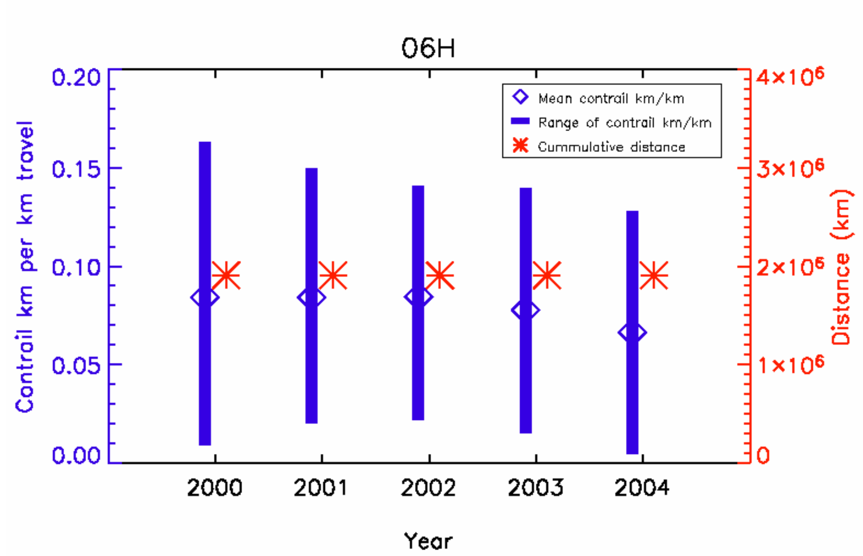

Figure 2 Calculated contrail for the 06H time period, disaggregated to show year to year variability. Each blue diamond represents the mean of 31 data values, with the blue bar indicating the range of values obtained. The total air traffic (red asterisk) and its distribution are kept constant, so variability in contrail between years reflects only changes in atmospheric conditions.

Contrail variability

The calculated contrail sensitivity for 6:00:00 NCEP for each January can be seen in Figure 2. The mean values (diamonds) vary from 6.6% (2004) of distance travelled to 8.5% (2002). This interannual variability in contrail sensitivity represents a range in annual mean contrail amount of 20% of the long term mean, even with no change in the amount or distribution of air traffic. The wide range of individual contrail sensitivity values recorded, from 0.4% (minimum 2004) to 16.7% (maximum 2000) of the distance travelled highlights the potential benefit of policies which could adjust in response to this variability to reduce the contrail produced while minimising the penalties incurred.

Vertical profile of contrail production

Figure 3 shows the calculated contrail sensitivity for 6:00:00 NCEP data, disaggregated by atmospheric pressure level. Following Figure 1, the bars indicate the range of values for the 155 January days considered and the diamond symbols indicate the mean. Again, the red asterisk is used to denote the distance travelled in the air traffic simulation, this time in the specified altitude layer. Of the four levels contributing substantially to the total calculated contrail coverage, the upper 3 (200hPa, 250hPa and 300hPa) show higher sensitivity than the 8% for the column as a whole. The sensitivity is greatest (14%) at 300hPa (30,000ft). At 150hPa, the contrail sensitivity is also above 10%, but contrail produced is low as the traffic sample contains few flights at this altitude. By contrast, at 400hPa (24,000ft) the mean contrail calculated indicates a mean contrail sensitivity as low as 2.3%.

This much lower typical propensity for contrail formation at lower altitudes has prompted the consideration of altitude restrictions as a means to reduce the climate impacts of aviation. However, the range of values obtained for contrail coverage at 400hPa is considerable; values are generally very low but punctuated by occasional high spikes of contrail formation with values above the mean occurring on only 6 to 10 days each month. There is also greater interannual variability at 400hPa than at higher altitudes (not shown).

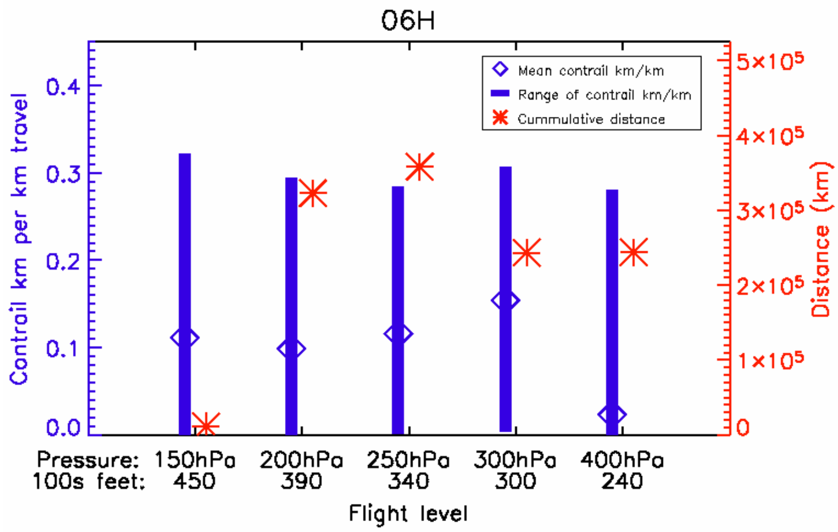

Figure 3 Calculated contrail for the 06H time period shown in Figure 1, disaggregated by pressure level. Each blue diamond represents the mean of 155 data values, with the blue bar indicating the range of values obtained. The red asterisk indicates the total distance travelled at that altitude by aircraft in the traffic sample during the six hour period.

DISCUSSION

The results presented here highlight the considerable variability in the production of contrail. This has strong implications for policies to address the impact of aviation on climate. Firstly, while applying a blanket altitude restriction could effectively reduce the mean contrail produced, significant further reductions could be obtained using an adaptive policy which allowed restrictions altered for days where contrail sensitivity at low altitude is unusually high. While this presents technical challenges for air traffic management and operational issues related to the difficulty to predict precise journey times in advance, the design of a policy which could adapt to atmospheric conditions to minimise the altitude restrictions required to substantially reduce contrail could reduce the penalties associated with altitude restriction by ensuring that unnecessary or counter-productive flight restrictions were not imposed. 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 effectively applied.

As a final note, the results presented here describe only variability in contrail sensitivity produced over a small region of Europe, and only for the month of January. Further analysis is required to explore the variability for other regions and other seasons before general conclusions about the applicability and effectiveness of proposed policies can be reached.

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