CONTRAIL AND CIRRUS CLOUD AVOIDANCE

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Keywords: *contrails, cirrus clouds, mitigation, environment, sustainability*

Abstract

Recent climate assessments have stressed the importance of perturbations in the Earth's radiation budget caused by air traffic. They are caused by the emission of greenhouse gases, aerosols, contrails and aviation induced cirrus clouds. The contribution from contrails and cirrus clouds might be larger than that of all other aircraft emissions combined. Facing an increasing demand in air travel, the challenge is to find technological and operational enablers for a more sustainable air traffic. A preliminary analysis of the proposed techniques is necessary for an adequate comparison. In this paper, an analysis tool is presented to compare different technologies regarding their environmental compability. A sample study is presented where the effect on block fuel consumption is examined if contrails were avoided by avoiding regions facilitating the formation of persistent contrails. For this purpose meteorological data is evaluated regarding persistent contrail formation.

1 Introduction

Aviation has been identified as contributor to anthropogenic changes in the Earth's radiation budget. In particular this is due to the emission of greenhouse gases, soot, aerosols, and the formation of contrails and aviation induced cirrus clouds. Linear persistent contrails occur in an ice supersaturated atmosphere if the Schmidt Appelman criterion is satisfied (1). Cirrus clouds can evolve from spreading persistent contrails known as primary cirrus or contrail cirrus (2). Secondary cirrus occur due to locally increased soot and aerosol concentration, which might lead to the formation of cirrus clouds that would not form in the absence of air traffic (3; 4; 5). An indirect climate forcing of aircraft emissions is possible by changing particle size and ice particle number density of natural cirrus clouds (6).

Aviation induced pollutants have been identified and assessed in terms of radiative forcing by the Intergovernmental Panel on Climate Change. Radiative forcing is a metric where the expected steady state equilibrium change in terms of global mean surface temperature is related linearly to the observed radiative forcing of a certain perturbation. Linear persistent contrails and aviation induced cirrus clouds were identified as main contributors to the overall aviation induced radiative forcing. It is estimated that linear persistent contrails contribute approximately 20% to the total aviation induced radiative forcing (7). This estimate considers a year 2000 scenario where cirrus clouds are excluded. Aviation induced cirrus clouds have the potential to cause a radiative forcing which exceeds the radiative forcing of all other emissions due to air traffic combined. Annually and globally averaged total contrail cover and the associated radiative forcing is expected to quadruple during the next decades due to the increase in air traffic (8).

Depending on the allocated importance of the radiative forcing due to persistent contrails and cirrus clouds relative to that of other aircraft emissions, it might occur that the avoidance of persistent contrails and cirrus clouds becomes the most important and pressing issue to be addressed in the future. The challenge is to accommodate the forecast growth in air traffic of 5% p.a. during the next decades (9; 10) whilst reducing the emission of greenhouse gases and aerosols, and mitigating the radiative forcing associated with persistent contrails and cirrus clouds. This can be achieved by introducing revolutionary technologies.

In order to assess technologies regarding their environmental impact, a tool has been developed combining engine performance, aircraft performance and meteorological data. It enables optimisation of the aircraft, engine and flight path for least fuel burn or other desired metrics.

In principle, persistent contrails could be avoided by avoiding regions in the atmosphere that support their formation (11). Avoiding the formation of persistent contrails would also avoid the formation of contrail cirrus clouds. This avoidance technique will in all likelihood cause an increase in block fuel consumption. In this paper, a sample study is presented examining the increase in block fuel consumption by avoiding regions in the atmosphere which support the formation of contrails. The departure and destination points considered are London and New York.

2 Model

Engine performance, aircraft performance and atmospheric data are combined in an integrated model. Therefore, multiple existing algorithms are linked with each other. They include Turbomatch, a Cranfield University gas turbine performance code (12), FLOPS, the NASA flight optimisation code (13), an ESDU aircraft performance code (14), and APPEM, a Cranfield University engine emission prediction code based on (15). Figure 1 shows the model with its modules. Optimisation can be carried out by varying the parameters of the different modules using different optimisation algorithms.

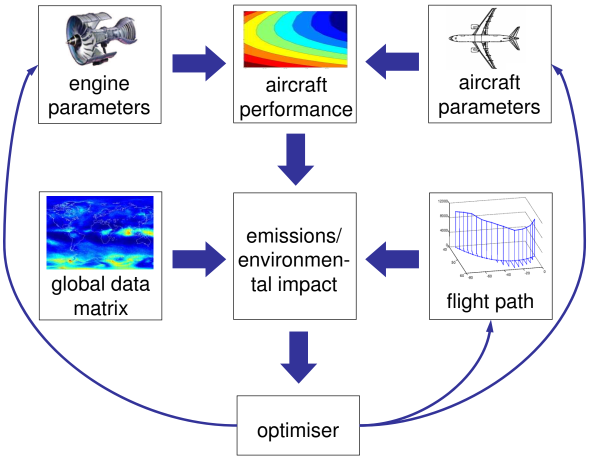


Fig. 1 model layout

In this study, flight path optimisation between specified departure and destination points for a given engine/aircraft combination is carried out in order to calculate the fuel burn penalty associated with contrail avoidance. Fuel consumption along the flight route is calculated considering a changing aircraft weight and the performance of the aircraft depending on altitude. Two optimisation algorithms are taken into account: genetic algorithms and the simplex search method. A description of the methodology applied during this study is given in the following sections.

2.1 Aircraft and engine model

Engine off-design performance is calculated for different throttle settings and altitudes. The considered engine represents a modern three spool high bypass ratio turbofan. Fuel flow and thrust for the different altitudes and throttle settings is stored in an engine deck. An aircraft performance table comprising inverse specific air range depending on altitude and the aircraft weight (percent fuel burned) is computed using the engine deck. The considered aircraft technology represents an advanced modern long-range mid-size subsonic transport aircraft for about 350 passengers. The performance table covers an altitude range from 6000 m to 12000 m with a resolution of 500 m, weight varies in 10 steps representing 100% fuel and 5% fuel. The calculated aircraft performance is given in figure 2, which shows inverse specific air range depending on altitude and aircraft weight for a fixed Mach number of 0.85.

Knowing the inverse specific air range for different altitudes and aircraft weights, it is possible to obtain the fuel burned during an entire flight path. During optimisation, linear interpolation is applied to calculate the inverse specific air range in between the sampled data points.

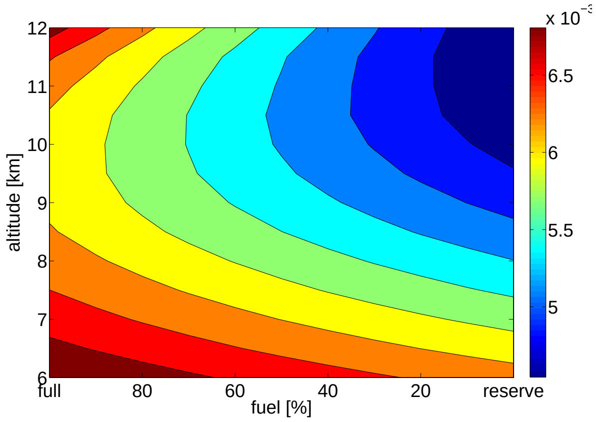


Fig. 2 Inverse specific air range [kg/m] calculated for a modern subsonic commercial transport aircraft at Mach number of 0.85.

2.2 Flight path parameterisation

In order to optimise the flight path for contrail formation and fuel burn, an adequate parameterisation of the flight path is necessary. The shortest connection between two points on the Earth's surface is defined by the great circle. Equally spaced points along the great circle between departure and destination on ground level define the base coordinates. The waypoints along the flight path are defined by the horizontal and vertical deviation from the base coordinates. The vertical deviation is the flight altitude whereas the horizontal deviation is a vector perpendicular to the great circle on ground level. Figure 3 shows the flight path (solid), the base coordinates on the great circle (dashed) and the deviation vectors (thin solid) in horizontal and vertical direction. Horizontal deviation for departure and destination is set to zero for all calculations.

Figure 4 shows the flight path projected on two dimensions. The variable parameters for flight path optimisation are the deviation vectors which determine the major waypoints. In order to increase the accuracy of the calculation, additional points are considered. They are equally spaced between the major waypoints, but only the major waypoints are accessed during optimisation.

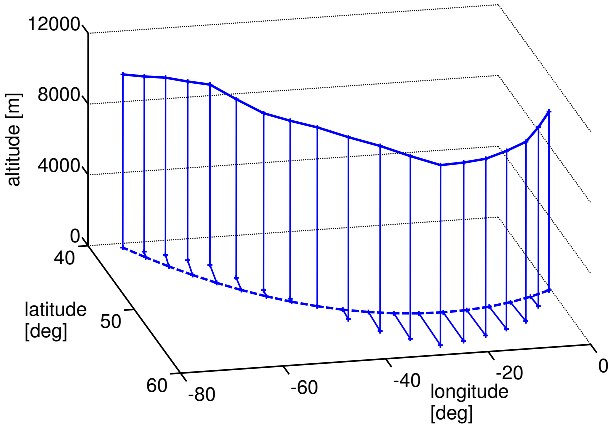


Fig. 3 Flight path parameterisation with base coordinates (dashed), the deviation vectors in horizontal and vertical direction (thin solid) and the flight path (thick solid).

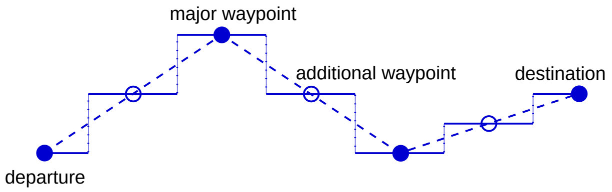


Fig. 4 Major waypoints and additional waypoints (solid and hollow circles) along the flight path (dashed). The flight path as considered for the calculation for fuel burn is shown by the thick solid lines.

For each waypoint, inverse specific air range and the probability of contrail formation is read from the aircraft performance table and the global data matrix. The fuel burned along the entire flight path is calculated starting at the destination point, which makes iteration redundant to match a given destination aircraft weight. Aircraft weight at destination includes 5% fuel reserves in this study.

2.3 Global data matrix

In order to calculate the fuel burn penalty associated with contrail avoidance, climate data for the year 2005 was evaluated regarding contrail formation. Analysis data from an unified field model has been made available by the MET Office. For the purpose of this study, data comprising temperature and relative humidity with respect to water was used. The grid resolution of the data sets is 432 in longitudinal direction and 325 in latitudinal direction at 19 pressure levels with a time step of 6 hours. Each grid point was evaluated regarding persistent contrail formation. It was assumed that persistent contrails occur in an ice supersaturated atmosphere if the Schmidt-Appelman criterion is satisfied (1).

If the mixing of the engine exhaust with ambient air is assumed to take place adiabatically and isobarically, it can be represented by a straight line on a phase diagram of water as shown in figure 5. The slope of the theoretical mixing line of the exhaust gases with ambient air on a phase diagram of water can be calculated from (16)

$$G_{theo.} = \frac{c_p \, EI_{H_2O} \, p_a}{(1-\eta_0) \, q_{net} \, \omega} \qquad (1)$$

where c_p is the specific heat capacity of air, EI_{H_2O} is the water emission index for a certain fuel, p_a is the ambient static pressure, η_0 is the overall engine efficiency, q_{net} is the fuel net calorific value and ω is the molar mass ratio water to air. The critical mixing line originates from the state in the atmosphere and tangents the saturation pressure line with respect to liquid water as shown in figure 5. Knowing the saturation pressure depending on temperature, its slope can be calculated iteratively. A contrail would appear if the theoretical slope of the mixing line exceeded the critical mixing line slope. Water saturation pressure is calculated using polynomials as given in (17).

Each grid point for each time step was examined regarding contrail formation with two possible outcomes: 0 if the criteria are not satisfied and 1 if the criteria are satisfied. The mean over all time steps results in the potential contrail cover for the year 2005, i.e. the probability that a contrail forms at a particular location in space during the observed period. An overall engine efficiency of 0.4 was assumed for all altitudes. The probability for contrail formation during the year 2005 is displayed on a world map in figure 6 for typical cruise altitudes (pressure levels). The data evaluation suggests that it is larger at the poles for lower altitudes and shifts toward the equator with higher altitudes.

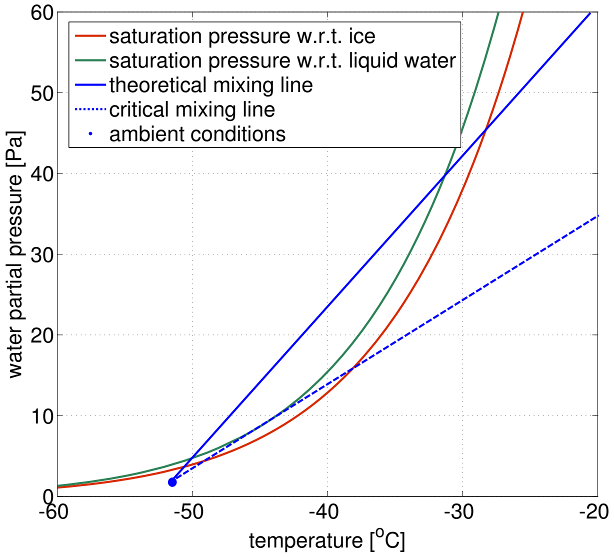
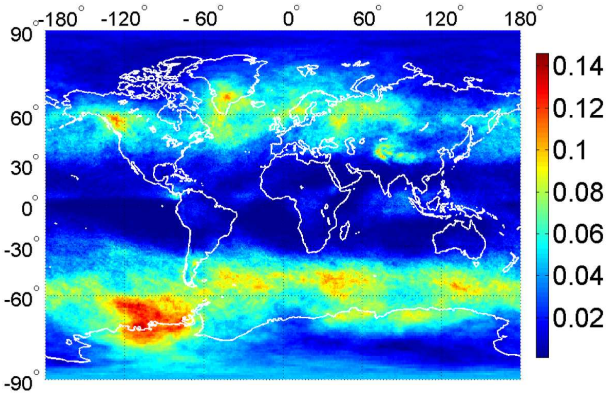


Fig. 5 The Schmidt Appelman criterion for contrail formation: A contrail appears if the theoretical mixing line slope is larger than the critical mixing line slope.

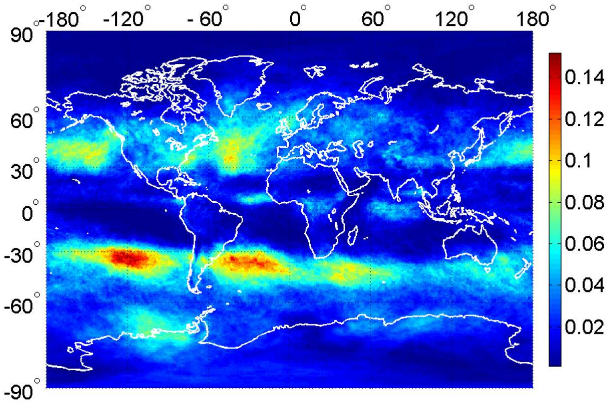
3 Optimisation

Two optimisation algorithms are considered for flight path optimisation, genetic algorithms and the simplex search method. Genetic algorithms are a particular class of evolutionary algorithms that use techniques inspired by evolutionary biology (18). The simplex search method is a direct search method that does not use numerical or analytic gradients (19).

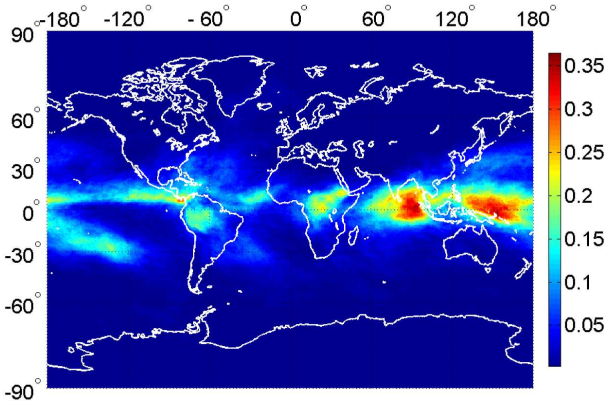
The probability for persistent contrail formation is taken from the global data matrix at each waypoint. Linear interpolation is applied in between the grid points. The objective of the op-



(a) 300 hPa (9164 m)



(b) 250 hPa (10363 m)



(c) 200 hPa (11775 m)

Fig. 6 Potential contrail cover for the year 2005 at different pressure levels.

timisation is to minimize fuel burn and reducing the fraction of the flight path for which contrails appear. An objective function has been selected which combines both, fuel consumption and contrail formation in the following form:

$$OBJ = m_{fuel}\ [c_w\ p_i + 1] \qquad (2)$$

where m_{fuel} is the mass of the fuel burned during the journey, c_w is a weighting factor and p_i is the fraction of the flight path for which persistent contrails appear.

The considered departure and destination points are London and New York with a distance of approximately 5600 km. Eight major grid points are considered. The number of additional waypoints is selected in order to match the grid resolution of the global data matrix.

4 Results and discussion

In the first instance, the flight path was optimised for minimum block fuel consumption. Contrail avoidance was not considered during this initial calculation. i.e. $c_w = 0$. The weighting factor was then varied between 1 and 10. Both the genetic algorithm and simplex search method converged for all calculations. Figure 7 shows the relative increase in fuel burn and decrease in contrail formation along the flight path for different values of the weighting factor c_w. If contrails were not avoided, approximately 2.5% of the flight path would occur in regions were the formation of persistent contrails is facilitated. The slope of the curve in figure 7 is relatively low in the beginning, so reducing contrails along the flight path from 2.5% to 1.5% implies a fuel burn penalty of less than 0.5%. However, the slope is becoming steeper and the increase in fuel burn is close to 2% reducing contrail appearance below 1%.

Flight altitude and horizontal deviation from the great circle are shown in figure 8. The flight altitude is reaches the maximum cruise altitude at some points above which the aircraft cannot operate. Horizontal deviation from the great circle becomes larger as the weighting factor increases. However, it remains small compared to the actual flight distance.

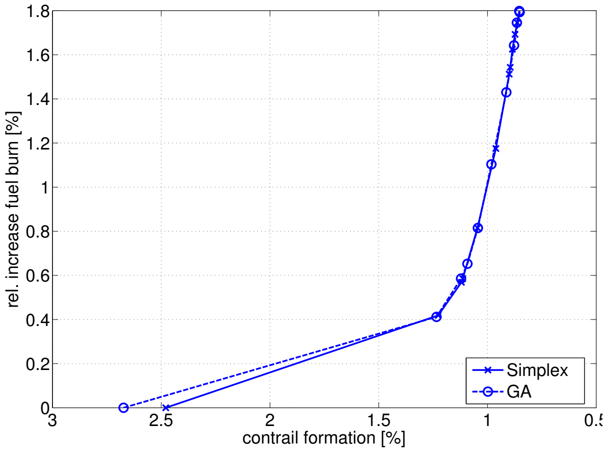
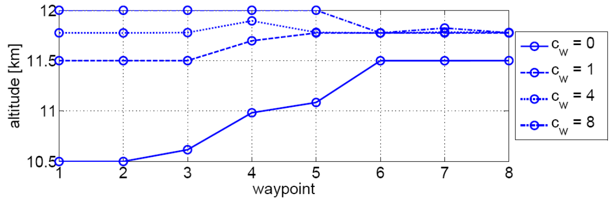
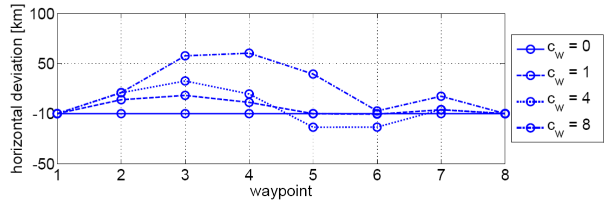


Fig. 7 Increase in fuel burn by avoiding contrails



(a) Flight altitude for different weighting factors.



(b) Horizontal deviation from the great circle for different weighting factors.

Fig. 8 The deviation vectors for different values of c_w.

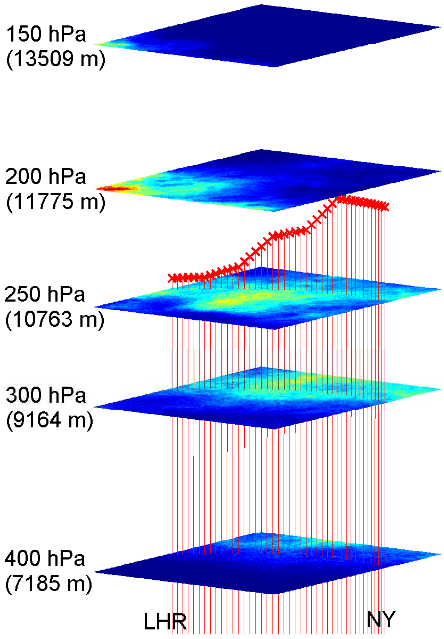


Fig. 9 Flight path and potential contrail cover for different altitudes.

Figure 9 shows the flight path for $cw = 0$ and the probability for contrail formation between departure and destination point. Cruise altitude always remains between two pressure levels for which contrail formation data is available. A higher vertical resolution of the meteorological data would be necessary to enable more accurate calculations.

The probability for contrail formation used herein represents an annual average. It is unrealistic to predict contrail formation potential over a long time period. Fixing the weighting factor to 6, optimisation is carried out for each month. Therefore, the probability for contrail formation for each month is calculated. This is followed by the optimisation of the flight path for that particular month. The results are given in figure 10. It can be seen that contrails appear more likely in the winter months. A reduction in contrail formation is possible but associated with a fuel burn penalty in the 1 percent range.

Contrails could be avoided using weather forecast data and calculating a flight path for least fuel burn and contrail avoidance prior the journey. Although this study considers annual and monthly data between London and New York, ac-

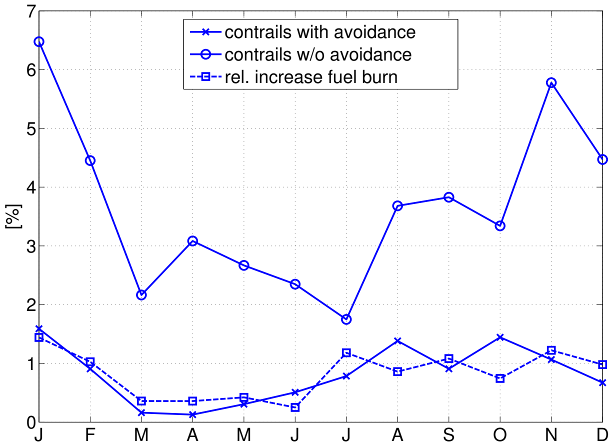


Fig. 10 Annual variation in contrail formation along the flight path with and without avoidance and the relative increase in fuel burn.

curate weather forecast data is available 24 hours in advance on a global basis. Air traffic management and safety issues associated with this technique of contrail avoidance may impede its application. Whereas free flight is less likely to be introduced over regions with heavy air traffic, it might still be an option for long haul flights.

Acknowledgments

This study is part of a Ph.D. project sponsored by the Cranfield Rolls Royce University Technology Center in Gas Turbine Performance Engineering.

The support of the Met Office and the BADC is greatly acknowledged.

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