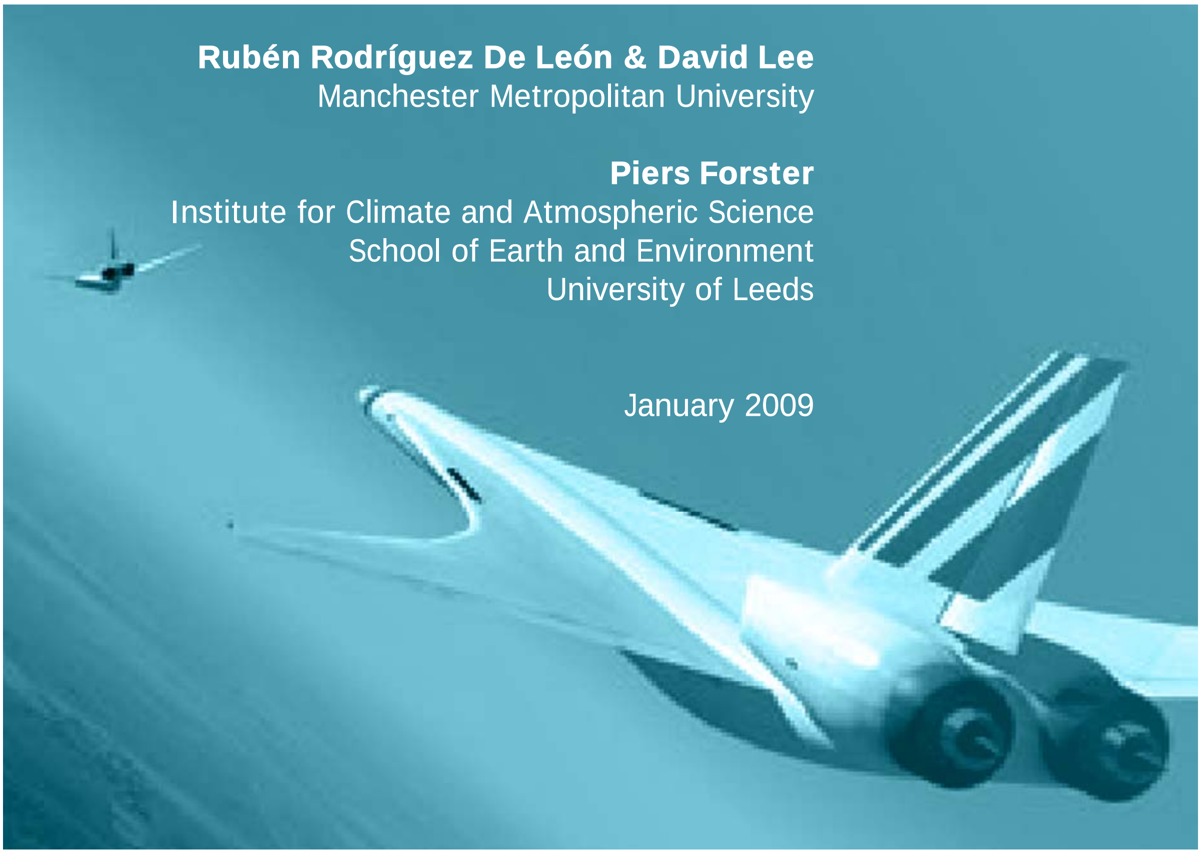
Aviation in a sustainable world Omega

# Climate Change

## Emissions and Impacts of supersonic BIzjets on the atmoSphere (EIBIS)



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## Omega

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## Executive Summary


The EIBIS project aimed to assess the climatic impact of the potential introduction of a fleet of Supersonic Business Jets (SSBJs) by analyzing the changes in the atmospheric radiation fields linked to the injection of water vapour and ozone (from NOx emissions) into the stratosphere as well as their associated induced cloud cover. This assessment is important to industry and policymakers in evaluating the potential environmental acceptability of such a fleet.

This report summarizes the activities undertaken by Manchester Metropolitan University (MMU) within the Centre for Air Transport and the Environment (CATE) in collaboration with the University of Leeds in setting up and linking the necessary models to calculate the climatic impact of supersonic traffic. These models include a chemistry transport and a radiative transfer application, together with a parameterization of contrail optical properties. The radiative transfer model was tested within an inter-comparison study in which its performance with subsonic and supersonic traffic simulations was assessed.

The three mentioned models are currently running at MMU's computing facilities, providing the necessary off-line tools to assess the climatic impact of present day and future air traffic. For present day traffic, our contrail radiative transfer model produced an estimated radiative forcing of 3 $mWm^{-2}$ (year 1992 traffic), which confirms, as other studies have, a strong reduction compared to IPCC's (1999) estimate. This new value is comparable to the water vapour forcing for the same year (1.5 $mWm^{-2}$) reported by IPCC.

The water vapour sensitivity tests performed within the radiative transfer code for supersonic traffic produced a 16% increase in the radiative forcing due to the shift of all current traffic from subsonic to supersonic cruise altitude. This forcing corresponds to a minimum percentage bound, while CTM runs with projected fuel flow information are needed in order to estimate how the longer stratospheric residence time of water vapour and its chemical interactions will increase its radiative forcing. The sensitivity tests for contrail optical properties showed that shifting traffic towards higher altitude within the subsonic cruise range produces reductions in the contrail radiative forcing by as much as 30% due to the change in the optical properties of ice crystals in colder regions, but at supersonic cruise altitudes the differences become negligible. Given the fact that a significant increment in the contrail cover from supersonic traffic is unlikely, water vapour would be the major contributor to a change in the radiative forcing from supersonic aircraft.

The estimated increase in the radiative forcing linked to the injected water vapour into the stratosphere requires further studies based on SSBJ engine performance and efficiency. The engine performance and fuel flow information will also allow the inclusion of SBBJ traffic into the contrail cover model in order to quantify the reductions with respect to subsonic traffic.

## 1.0 Introduction

The environmental impact of any supersonic aircraft is likely to be of major public concern, since previous research dating back to the late 1960s has highlighted the potential impact on ozone depletion and climate change. Thus, the sensitivity, even to a relatively small fleet of SSBJs, will be high. IPCC (1999) estimated that the partial replacement of subsonic aircraft by supersonic aircraft may lead to a 50% larger radiative forcing in 2050. The aim of the current study is to develop the necessary tools to model the major impacts of supersonic traffic on the planet’s energy balance.

Aircraft emissions of CO2, NOx, and water vapour linked to the introduction of SSBJs would depend on parameters like fuel flow and cruise altitude, which differ from those of subsonic aircraft. The chemical and radiative impact of NOx and water vapour emissions in the stratosphere strongly depends on cruise altitude due to the differences in the humidity and ozone concentration profiles between the stratosphere and the troposphere as shown in figures 1 and 2.

NOx acts as a precursor of two greenhouse gasses, O3 and CH4; the chemical reactions involved in the production of these gases do not only depend on NOx emissions but on the background atmospheric composition, on the altitude at which they are injected, and on the local insolation. In order to calculate the impact of NOx emissions on the atmosphere, a Chemistry Transport Model (CTM) capable of treating both the troposphere and the stratosphere is needed. CTMs are complex models with demanding computing and maintenance requirements, which require climatological information about the atmospheric composition and dynamics. In the following section we describe the implementation of a sophisticated CTM and background climatology at MMU.

## 2.0 Chemistry transport model setup

After investigating the performance and possibilities of different models, a global chemical transport model for ozone and related chemical tracers (MOZART, version 3) was chosen and setup at MMU’s state-of-the-art NEC vector supercomputer. A background atmospheric climatological data base specifically produced for MOZART was implemented with help from the Institute of Chemistry and Dynamics of the Geosphere in Jülich, Germany. The CTM was tested on site and spin up runs were performed in order to produce stable start up gas concentration files.

MOZART proved a valuable tool to assess the chemical impact of aviation on the atmosphere; it is currently running at MMU with its full functionality, providing information of the coupled chemical and dynamical interaction of emissions in the troposphere and the stratosphere.

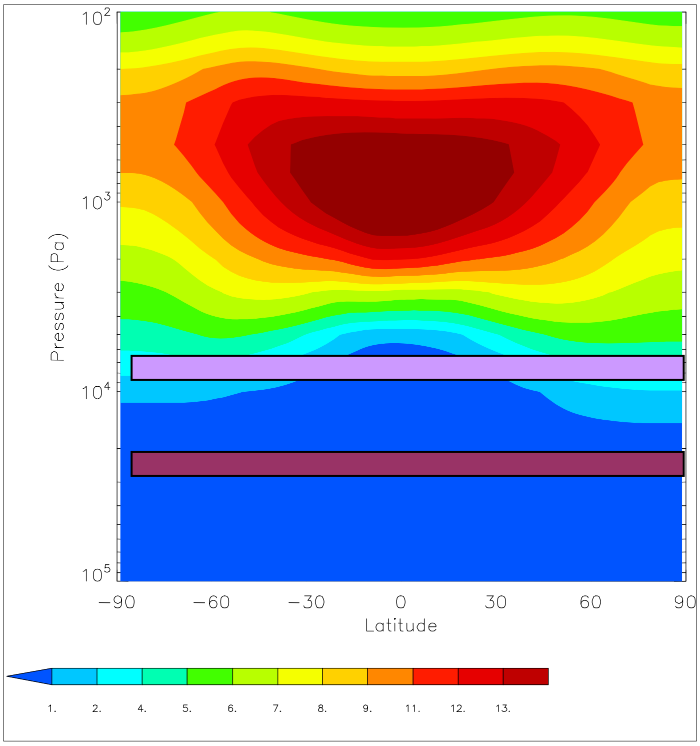


**Figure 1 – Annual averaged ozone mixing ratios (mg/kg) as a function of pressure and latitude. Approximate subsonic and supersonic cruise altitudes shown in purple and lilac respectively.**

# 3.0 Radiative impact of greenhouse gas changes.

## 3.1 Radiative transfer model setup

The calculation of the radiative impact of the greenhouse gas changes provided by MOZART requires a global-scale radiative transfer model (RTM). The UK's Met Office two-stream radiative transfer code (EDWARDS AND SLINGO) was setup and tested using idealised cases relevant to SSBJ impacts.

As a sensitivity test, we compared the radiative forcing of present-day water vapour emissions at subsonic and supersonic cruise altitudes (200 hPa and 100 hPa) without natural background clouds. The results showed an increase in the water vapour radiative forcing by 16% with respect to the current subsonic fleet using a mid-latitude summer single column atmosphere. This increase in the greenhouse effect is explained by the differences in the natural humidity at subsonic and supersonic cruise altitudes shown in Fig. 2. Further studies with detailed cruise altitude and fuel flow are needed in order to determine the effect of the longer residence time of water vapour in the stratosphere and its chemical interactions on its radiative forcing.

In order to perform realistic global scale calculations a database including atmospheric composition, cloud cover and surface reflectance was implemented into the RTM with help from the University of Leeds based on the International Satellite Cloud Climatology Project (Schiffer and Rossow, 1983). The validation of the RTM and the climatology is described in the following section.

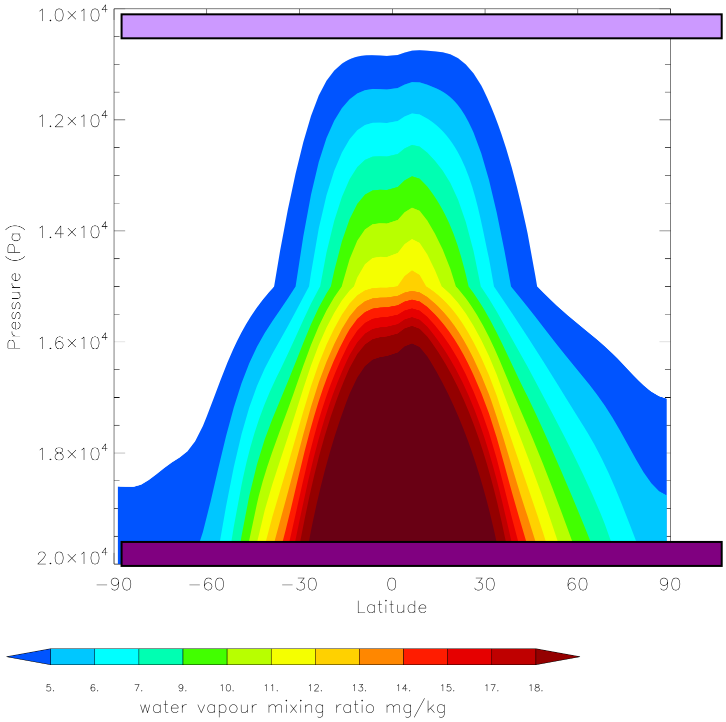


**Figure 2 – As in Fig. 1 but for water vapour.**

## 3.2 RTM testing (water vapour forcing calculations)

The performance of the Edwards and Slingo code and the background data base were tested against other six radiative schemes including line-by-line codes and general circulation models (GCMs) in an inter-comparison experiment part of the EU QUANTIFY project (http://www.pa.op.dlr.de/quantify/), funded by the European Commission within the 6th research framework programme. The benchmark cases included single column as well as global-scale calculations of the impact of stratospheric water vapour injected by subsonic and supersonic aircraft.

In order to compare the model output for supersonic water vapour emissions, global radiative transfer calculations for an increase in stratospheric water vapour from 3.0 to 3.7 ppmv were performed, we submitted our results in collaboration with the University of Leeds. Due to time constraints we did not participate in the comparisons involving the calculation the radiative impact of 2050 air traffic.

The single column results from the different participating models produced a range of net forcings between 0.2 and 0.4 $Wm^{-2}$ for the idealised 3.0 to 3.7 ppmv concentration increase, and between 0.035 and 0.050 $Wm^{-2}$ for 2050 subsonic and supersonic traffic, implying a factor of 2 in the uncertainties amongst the models for stratospheric water vapour calculations. The results of the inter-comparison are described in the article (see attached document and bibliography) by Myhre et al. submitted to Meteorologische Zeitschrift.

# 4.0 Radiative impact of contrails

## 4.1 Context

Contrails have been estimated to cover approximately 0.1% of the planet with a factor of 2 or 3 uncertainty. Supersonic aircraft are expected to form few persistent contrails because the probability of ice-supersaturated air at supersonic cruise altitudes is small. An off-line model is being developed at MMU to calculate global contrail cover using atmospheric data from the European Centre for Medium-Range Weather Forecasts with a 3 hour temporal resolution. An article describing the methodology of the contrail cover model is currently in preparation.

The optical properties of ice clouds are in general highly simplified in large scale models due to the computational expense of detailed calculations, many GCMs still use fixed optical properties for ice clouds, but in order perform sensitivity studies on contrail radiative forcing, a sophisticated representation of the microphysical and optical properties of ice crystals is needed. In the following section we describe the implementation of our contrail model in the RTM.

## 4.2 Contrail model setup

The Ice Water Content (IWC) of cirrus clouds and contrails observed during the mid-latitude field campaign CIRRUS III (Schäuble et al., 2008) showed that the IWC is similar in cirrus and contrails under the same atmospheric conditions. We assumed in our study that the properties of persistent contrails will not differ substantially from those of natural cirrus. Based on this assumption, a parameterization within the Edwards and Slingo model was produced to predict contrail physical and radiative properties as a function of their temperature by introducing cirrus ice water content climatological data and middle latitude cirrus ice crystal size retrievals.

In order to resolve contrail physical thickness we refined the RTM's background data and the model's layer depth between 24,000 and 40,000 feet. The total cloud water mass was separated into its liquid and solid phases using an ice water climatology (Schiller et al. 2008) based on tropical, middle and high latitude airborne measurements.

The size of the ice particles was included in our model using Donovan's (2003) parameterization of cirrus size distributions, based on lidar and Doppler-radar data from the Atmospheric Measurement Progran's Southern Great Plains site in central USA, which defines the effective size of cirrus particles in terms of the total IWC and the cloud's temperature. Our parameterization predicts the microphysical properties of natural cirrus and contrails as a function of the cloud layer's temperature, providing a sophisticated diagnostic tool to calculate the radiative properties of contrails within the RTM.

## 4.3 Contrail radiative tests

The inter-comparison tests in the QUANTIFY experiment included contrail radiative calculations for single column cases and global scale 2050 traffic. For an assumed 1% homogeneous contrail global cover the different models produced a radiative forcing range from 0.10 to 0.18 $Wm^{-2}$. Due to time constraints we did not run the 2050 traffic case, for which the inter-comparison models produced a radiative forcing range between 0.0093 and 0.0150 $W^{-2}$, indicating a smaller uncertainty than the one observed in the stratospheric water vapour calculations.

A sensitivity study for present day subsonic contrail forcing on altitude was performed independently; the results are presented in the following section.

## 4.4 Contrail results

The results for current subsonic traffic are shown in Fig. 3. A net contrail radiative forcing of 0.003 Wm-2 was estimated. It is important to point out that current knowledge of aircraft induced cloudiness only includes so called "linear contrails", which correspond to the minimum increase of cloudiness linked to aircraft. The extent of the total aircraft induced cloudiness is still unknown and might be significantly larger than that of linear contrails.

In order to perform a sensitivity test of the relative forcing by SSBJ contrails with respect to subsonic traffic, we shifted the representative subsonic cruise altitude from 34 000 ft to 52 000 ft, which produced a radiative forcing reduction of only 0.3% for present day traffic assuming the same contrail cover. Very small differences are also expected from supersonic contrail cover.

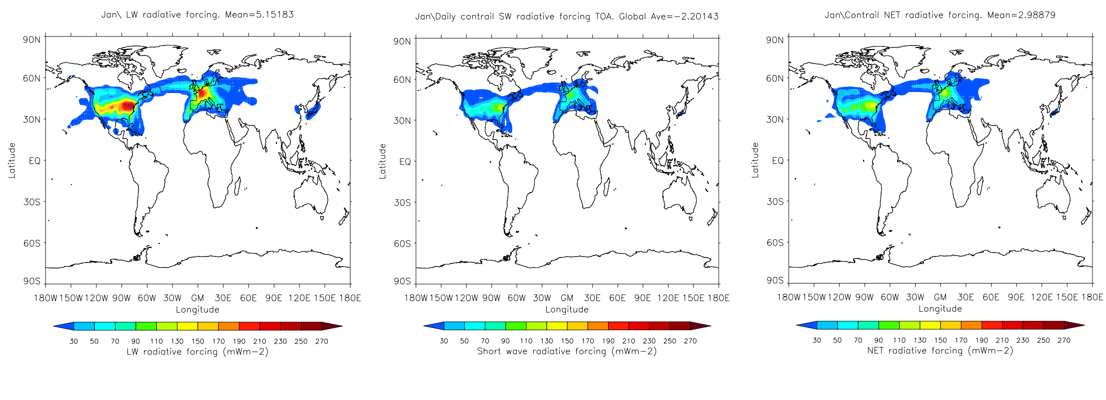


**Figure 2 – Long Wave, Short Wave and NET (LW +SW) radiative forcing maps of contrail forcing (the colourbar in the SW map uses the absolute value of the forcing).**

## 5.0 Conclusions

This initial OMEGA study has developed a capacity for studying supersonic aviation-climate effects. A chemistry transport and a radiative transfer model were setup and tested to calculate the effect of stratospheric emissions of NOx, water vapour and contrails. A radiative contrail parameterization was produced and a contrail cover model is under development.

The CTM is currently up and running at MMU, providing coupled tropospphe-stratospheric chemistry transport calculations that allow the inclusion of supersonic traffic. The RTM provides radiative forcing calculations for the CTM's output and for water vapour emissions in the stratosphere. A sophisticated parameterization was developed for the microphysical properties of contrails that can realistically predict the impact of stratospheric clouds.

The sensitivity studies performed indicate negligible radiative forcing differences with respect to subsonic aircraft with respect to linear contrails. The corresponding increase in the radiative forcing linked to the injected water vapour into the stratosphere requires further studies based on SSBJ engine performance and efficiency. The engine performance and fuel flow information will also allow the inclusion of SBBJ traffic into the contrail cover model in order to quantify the reductions with respect to subsonic traffic.

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