Aircraft emissions and air quality of the tropopause region – a model study of the North Atlantic flight corridor

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Abstract

Aircraft emissions can affect the tropopause region through their impact on chemical and radiative processes. They may thus play a peculiar role for anthropogenically induced modifications of the Earth’s climate. The effect of subsonic aircraft emissions on the chemical system of the tropopause region is investigated using a special version of the European Air Pollution Dispersion Model (EURAD). Simulations have been carried out for the North Atlantic flight corridor. The role of the composition of the background atmosphere is analysed in particular. The results show a clear dependence of ozone changes as induced by aircraft exhaust on background aerosols. Furthermore, it is argued that mesoscale dynamics, i.e. tropopause foldings, cut-off lows and streamers causing variations of the background composition at cruise altitudes, may modify the efficiency of ozone formation through aircraft emissions.

1 Introduction

Many studies exist which address the global effect of aircraft emissions on climate and thus the environment. Available estimates of the magnitude of possible impacts on the atmosphere are subject to a large number of uncertainties regarding factors and processes controlling changes in atmospheric composition due to airtraffic and
their consequences.

One of the areas where better understanding of the processes leading to chemical transformation and to dilution of primary and secondary aircraft exhaust products is required is mesoscale dynamics of the atmosphere at long-range cruise altitudes. At middle latitudes it happens that the majority of subsonic flights which are only considered in this study occurs in the tropopause region (Hoinka et al., 1993). This makes the evaluation of the impact of aircraft exhaust a scientifically intriguing and methodologically complex problem. The reason is that chemical transformation of the main reactive component of aircraft emissions, namely NO\textsubscript{x}, and related ozone production strongly depend on the (tropospheric or stratospheric) character of the background atmosphere where the emissions are released (e.g. Ehhalt and Rohrer, 1995; Lippert, 1996; Hendricks, 1997). Similar considerations hold for the problem of contrail formation (Ponater et al., 1996; Sausen et al., 1998) which heavily depends on relative humidity. As it is well known this parameter exhibits strong vertical changes in the vicinity of the tropopause and also in the horizontal direction.

Dynamical processes causing strong time dependence of these features are characterized by tropopause foldings, cut-off lows and streamers over a wide range of latitudes in the tropopause region (Ebel et al., 1996; Elbern et al., 1998; Kowol-Santen, 1998). This study is focusing on spatial scales where such phenomena play a significant role. Mesoscale features of air traffic effects on the tropopause region over the North Atlantic have been investigated using a chemical box model and a three-dimensional model system adapted to the specific conditions existing at these atmospheric levels. The model is briefly described in Section 2. Some results of box and mesoscale model simulations are presented and discussed in Section 3 and conclusions regarding the role of mesoscale effects are given in Section 4.

2 The Model

Episodic simulations of aircraft emission impact over the North Atlantic have been carried out with a special version of the European Air Pollution Dispersion (EURAD) model system (Petry et al., 1994, 1997; Ebel et al., 1997). It has a refined vertical resolution around the tropopause and covers the troposphere and lower stratosphere up to
10 hPa. The horizontal grid size is usually chosen to be 50 x 50 km². A chemical mechanism (CHEST: Chemical mechanism for the lower Stratosphere and Troposphere; Lippert, 1996; Hendricks, 1997) especially designed for the treatment of aircraft emission transformation at subsonic cruise altitudes has been employed. It is based on the RADM2 mechanism (Stockwell et al., 1990). The Penn State/NCAR Mesoscale Model Version 5 (MM5, Dudhia, 1993, Grell et al., 1993) is used as the meteorological model of the EURAD system.

Emission estimates are based on the global inventory of aircraft air pollutants emissions by McInnes and Walker (1992). ECMWF analyses are employed to formulate initial and boundary conditions for the meteorological part of the EURAD system. Chemical box calculations have also been carried out using the CHEST mechanism.

3 Results and Discussion

Only a limited number of results obtained from chemical box and three-dimensional simulations can be discussed in this short study. They are selected with emphasis on mesoscale transport and mixing effects and height dependence of chemical transformation of aircraft NOₓ emissions and thus ozone perturbations. Since mixing efficiency also changes significantly with altitude around the tropopause both processes, namely chemical transformation and mesoscale eddy transport, are intimately coupled and require joint treatment in complex three-dimensional studies. Nevertheless, since field experiments seldom provide the desired complex information and the isolated numerical treatment of special processes may help to gain better insight in the development of aircraft induced perturbations, two important aspects of transport and chemical transformations are discussed on the basis of separate chemical and dynamical numerical experiments.

Using the chemical box model CHEST it can easily be demonstrated how ozone productivity due to aircraft induced NOₓ perturbations depends on altitude or pressure, season or solar inclination and background NOₓ concentration (Fig. 1) which may be controlled by overall air traffic, upward transport of polluted air from the atmospheric boundary layer and various natural NOₓ sources. It is evident that higher cruise levels corresponding to lower pressure levels result in a reduction of net additional ozone generation if background NOₓ is below about 0.12 ppbV. Above this threshold a net reduction of
Figure 1: Box calculations with CHEST showing the dependence of net ozone production around noon at 50° N on background NOx concentration (horizontal axis, ppbV), season and pressure (altitude). (Lippert, 1996)

ozone production due to NOx concentration increases caused by air traffic is expected.

The question is as to how long a polluted air parcel with increased ozone concentration can reside at a given level. Usually, downward transport leads to faster removal of ozone from the atmosphere so that higher efficiency of ozone generation at lower levels may be counteracted by stronger transport removing the ozone perturbation. At middle latitudes, i.e. in the North Atlantic flight corridor, the appearance of tropopause foldings, cut-off lows and streamers plays an important role in this context. Fig. 2 exhibits an example of the development of a tropopause folding, cut-off low and streamer-like fine
Figure 2: Example of mesoscale transport and mixing over the North Atlantic, on the 310 K isentropic level, 7 February 1997, 12 UTC to 8 February, 1997, 12 UTC. The change of potential vorticity (PV) contours is shown. Range of PV: 2 to 5 PV units. The method of contour advection was employed.
scale structures in the tropopause region and upper troposphere (310 K isentropic level). It is obvious that such meteorological conditions may heavily control the chemical fate of an air parcel contaminated by air traffic emissions. As regards vertical transport of air mass and minor constituents by such events it should be noted that not only downward but also upward fluxes are generated. At the tropopause the mentioned phenomena usually lead to net downward transport. Yet under anticyclonic conditions a net upward cross-tropopause flux may be generated. The overall importance of this feature of mesoscale circulation for the development of aircraft induced ozone perturbations still needs to be investigated.

The integral effect of dynamics and chemistry in the North Atlantic flight corridor has been simulated with the EURAD system for a large variety of episodes. A convenient way to assess the impact of air traffic on the upper troposphere and lower stratosphere proves to be the estimation of total net ozone production over a specific area (in this case the north-eastern part of the North Atlantic). Large variability of the absolute change of the total ozone mass has been found. Slight decreases up to about 100 tons have been obtained for autumn conditions whereas increases of 1000 tons or more appear to be possible during summer (Fig. 3). Interestingly, the ozone budget perturbation significantly depends on the aerosol burden of the tropopause region. It tends to increase net aircraft-induced ozone production due to its impact on background \( NO_X \) concentration and on catalytic cycles (Hendricks et al., 1999).

4 Conclusions

At present the impact of air traffic exhaust on climate and composition of the atmosphere does not seem to be problematic though global model estimates have identified a slight increase of radiative forcing of the climate and ozone concentration near the tropopause at midlatitudes up to about 5% of the present background values. Yet the expected strong increase of air traffic in the near future, including supersonic flights, may lead to noticeable and unwanted effects regarding global change (Dameris et al., 1998; Schumann et al., 1997; Brasseur et al., 1998; Grewe et al., 1999). To arrive at a reliable prediction of these effects better understanding of the role of mesoscale factors is required. This may also help to develop an air
**Figure 3:** Absolute change of ozone mass (tons) due to air traffic emissions calculated for the lowest stratosphere and upper troposphere (between about 160 and 400 hPa) over the northeastern part of the North Atlantic flight corridor (domain size 6.44 \( \times \) 10^6 km^2). Continuous line: without heterogeneous reactions; broken line: with heterogeneous reactions. Episode 28 July - 4 August 1994, emissions starting at 28 July, 00 UTC.

Traffic strategy which allows an increase of flight frequencies without a too strong growth of aircraft emission impacts by exploiting the mesoscale characteristics of the atmosphere around the tropopause.

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References


Air Pollution


Petry, H., Lippert, E., Hendricks, J. & Ebel, A., Simulation of trans-


