

Aviation, Atmosphere and Climate - What has been learned

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ABSTRACT: High-lights of the Conference "Aviation, Atmosphere, and Climate" in Friedrichshafen, Germany, June 30 to July 3 2003 are summarized based on a personal view of the author. The aviation induced cirrus changes were in the center of this conference. Initiation of an amendment to the IPCC assessment including assessments of other traffic modes is recommended.

1 INTRODUCTION

In the long term, the impact on climate change is the most important environmental effect of aviation (Green, this conference). The impact of aircraft emissions on the global atmosphere has been assessed under guidance of the Intergovernmental Panel of Climate Change in 1999 (IPCC, 1999), see also Schumann et al. (2001). This conference saw many papers adding considerably to our understanding and revising some of the conclusions given in earlier assessments. The present paper summarizes the talk given at the end of the Conference based on material circulated before the meeting and the material presented at the conference.

2 REVISION OF THE IPCC ASSESSMENT

2.1 Subsonic aviation

According to IPCC (1999), the global mean radiative forcing by air traffic in 1992 was 0.05 W/m^2 . The contrail radiative forcing (RF) was estimated for an optical depth of the contrail cirrus of 0.3, contrail cloud cover of 0.087 % and fixed flight level (200 hPa). The cirrus cloud effect was not quantified but estimated from cirrus trends in correlation with air traffic. The given total did not include cirrus change. ICAO expected a 5 to 10-fold rise of air traffic until 2050, for which the RF was expected to increase by a factor of 4.

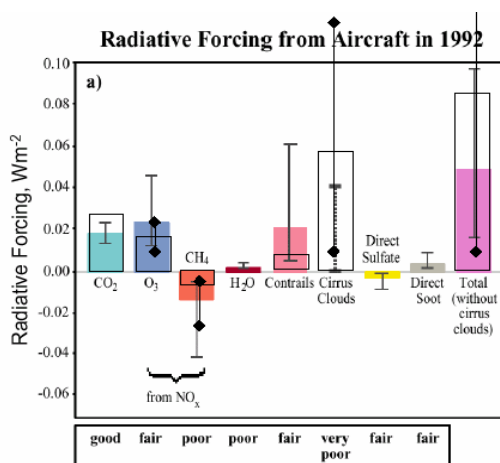


Figure 1. Radiative forcing (RF) from air traffic in 1992 from IPCC (1999; colored columns and bars with end-lines) and revised estimates (white columns and bars with diamonds) based on recent research results (EU-project TRADEOFF, papers by Marquart et al (2003), Mannstein, and others at this conference). The revised RF from CO₂ applies to the year 2000. Note that the revised total now includes the cirrus clouds.

Based on TRADEOFF and other studies (such as related papers), a revised RF figure can be suggested as shown in Fig. 1. The major changes come from a reduced optical thickness of line-shaped contrails, and first estimates of aviation induced cirrus cover changes. The revised RF value given for CO₂ in this figure, which is larger than the value given in the previous assessment for 1992, applies to the year 2000.

The level of scientific understanding has not changed significantly. For example, the scientific understanding of O₃/CH₄ changes, which was classified as "fair/poor" in IPCC (1999) can, to the authors opinion, not yet be classified as being "good/fair": The present models all use similar emission assumptions for CH₄ and hydrocarbons, hence they may not yet include all uncertainties from emissions from the biosphere on the CO/OH/CH₄ budgets. Also, the treatment of vertical mixing in and out of the boundary layer is not well treated in the models.

It was suggested to no longer distinguish between line-shaped contrails and cirrus changes in the future. Instead one should have one bar for contrail effects (the direct effect) and one bar for the aerosol induced cirrus change effect (the indirect effect) in the future.

2.2 *Supersonic aviation*

IPCC (1999) concluded that 1000 high speed civil transport (HSCT) aircraft, with an EI(NO_x) of 5 g/kg, flying at Mach 2.4, would cause 0.5 % O₃ column reduction, O₃ reduction occurring mainly above 19 km altitude, strong contribution from H₂O emissions to O₃ reduction, large importance of sulfate loading, and a RF up to 0.1 W m⁻², mainly from H₂O increases.

The impact of supersonic aircraft on radiative forcing is smaller than assessed by IPCC (1999). For the same HSCT fleet, recent studies suggest a 3 % O₃ column reduction, O₃ reduction mainly above 15 km altitude, strong contribution from NO_x to O₃ reduction, a reduced importance of sulfate loading, and a RF of up to 0.05 W m⁻², mainly from H₂O increases.

3 EMISSIONS

Many new results have been presented from projects such as PARTEMIS, EXCAVATE, and PAZI. Soot gets hydrated and may act as IN also without fuel sulfur. The hygroscopicity of soot increases with fuel sulfur content, so that soot may act more easily as cloud condensation nuclei (CCN) when burned from fuels with high sulfur content. Soot particles may contribute CCNs and also ice nucleation nuclei (IN) to the upper troposphere and lower stratosphere (UTLS). Fuel sulfur increases the number of ice particles formed in contrails but the increase in the number of ice particles formed is far less than linear in the fuel sulfur content (found in experiments SULFUR and AIDA). A lower reaction rate for SO₂ with OH has been computed (Zellner et al.). The finding implies that a considerable fraction of the SO₃ found experimentally to be emitted from engines must have been formed in the combustor; this needs to be further investigated. The conversion fraction of fuel sulfur to H₂SO₄ increases slightly with power setting and most results indicate values of 1 to 5%, i.e. far less than expected a few years ago. Engines emit electrically charged ions formed in the combustor (chemi-ions, Cis), which turn more easily than neutral particles into CCNs after growth by uptake of condensing sulfuric acid and of other condensable gases, but an increase in CCNs in the free atmosphere due to CIs emitted from aircraft has not yet been observed in the real atmosphere. Engines emit organic volatile material, the amount increases with power setting. Hydrocarbon measurements have been presented (e.g. Kurtenbach et al.; e.g. from PARTEMIS). It is recommended that the data get classified into condensable and non-condensables. Considerable progress has been made in modeling soot formation. The results have been compared successfully with laboratory measurements. A new test facility has been developed to study soot formation at pressure values representative for real engines. But real engines (with complex details of geometry and high pressure) are not yet modeled and measured realistically. Hence, soot formation and the composition of emissions at combustor exit (such as OH, SO₃) need further investigations.

4 OZONE AND METHANE

Many new results have been presented from projects such as TRADEOFF. Data from previous UTLS experiments have been made available without grid averaging for model validation. New data are becoming available on CO, NO, NO_y and others from the projects EULINOX, INCA, CARIBIC, MOZAIC, CRYSTAL-FACE etc. Chemical transport models (CTMs) have been improved, with respect to dynamics and chemistry, and now include tropospheric and stratospheric chemistry consistently. However, the results from various state-of-the-art CTMs still show large variability, mainly because of insufficient resolution, unknown background concentrations, and different treatment of heterogeneous chemistry on aerosols and ice. The largest uncertainty in background NO_x stems from unknown contributions from lightning. Modeling transport near the tropopause may require very high resolution (see below).

With inclusion of heterogeneous processes on aerosols and ice, the NO_x impact on ozone is smaller than for pure gas phase chemistry. The impact of NO_x on CH₄ life time appears to be smaller than assessed in IPCC (1999). This size of this impact depends strongly on the representation of vertical transport in the troposphere in the CTMs.

The question of how far the RF due to increased O₃ and reduced CH₄ cancel each other with respect to climate impact (changes in surface temperatures etc.) has still not been determined in spite of the fact that the tools (global circulation models) required for such studies do exist now; it is suggested to study this effect now with the existing tools.

The climate impact (change in surface temperature etc.) is only approximately proportional linearly to the radiative forcing. Recent studies show that ozone increases in the UTLS have a stronger impact on climate than expected from the RF value.

Plume processes occur at scales of meters to kilometers and are, therefore, not directly resolved by large scale CTMs. The plume process details are not included in most of previous CTM/GCM studies. Instead most CTMs assume that the emitted species get mixed over the respective grid box (with horizontal scales of the order 10 to 300 km and vertical scales of the order 1 km) of the model immediately after emissions. Details of plume processes are important for conversion of NO_x to NO_y and for ozone formation and important for ice formation in plumes. Most of the plume processes that lead to contrail formation are sufficiently well understood. With respect to NO_y and O₃ chemistry, the various studies find very different importance of the impact of plume (Plumb, this conference, and Kraabøl et al. (2002) find either 3 or 18 % change in ozone formation due to plume processes). Although this uncertainty is only a small part of the total uncertainty of present CTMs, the impact of plume processes on air chemistry needs further clarification.

With respect to emissions from supersonic aircraft in the mid stratosphere, the change in the reaction rates found for reactions of NO_x with OH implies a larger importance of NO_x emissions and a reduced importance of H₂O emissions for stratospheric ozone destruction.

5 AEROSOLS, CONTRAILS AND CIRRUS

Aircraft emit gases and particles which influence cloud formation. Two kinds of effects of aircraft emissions on cloud formation can be distinguished: 1) by spreading contrails in supersaturated air masses (the direct effect), and 2) by aerosol from aviation accumulated in the UTLS over several days affecting cirrus properties (the indirect effect). The direct effect is clearly visible to ground observers and observations by satellites from space. The indirect effect has not been identified in observations in the real atmosphere but has been identified from numerical simulations. The indirect effect may induce positive or negative RF.

This topic was at the center of the present conference. Many new results have been presented from projects such as INCA, CRYSTAL-FACE, PAZI, PARTS, and others. The direct effect was discussed in several papers at this conference in terms of line-shaped contrail and cirrus changes in correlation to traffic in the last few hours. The indirect effect (from sulfuric acid droplets and soot) and their treatment in cirrus models was discussed with respect to aviation impact for the first time. The observed long-term cirrus changes, as discussed by Zerefos et al. (see also IPCC, 1999; and Minnis et al., 2003), are due to the combined direct and indirect effects.

Aerosol and cirrus differences in clean/dirty air masses (as found in the INCA experiment) support the assumption that differences in aerosols may cause changes in cirrus cloud properties, but cirrus formation depends also strongly on the vertical motions in the atmosphere.

Ice forms homogeneously from solution droplets or heterogeneously by interaction of liquid and solid particles at ice saturation above 100 % and below the critical humidity for homogeneous nucleation (near about 160%). Soot represents an important fraction of aerosol in the UTLS (see Baumgardner et al., this conference). Biomass burning in the tropics and aviation contribute considerably to the soot number density in the upper troposphere. Soot may induce heterogeneous ice nucleation and hence may represent the most important aviation aerosol impacting cirrus formation, but the quantitative effect is still to be determined. Modeling of heterogeneous nucleation of cirrus crystals is now becoming feasible but the models are still in their infancy. New data on the HNO_3 deposition on ice become available (important, e.g., for washout and denitrification of the polar stratosphere):

The cover by line-shaped contrails has been computed for given traffic and temperature/humidity fields. However the results are not yet in sufficient agreement with observations; instead contrail cover is found to be non-linearly related to traffic density. The largest contrail cover occurs even for weak traffic density in regions with high potential contrail cover.

Results presented at this conference confirm that aviation has caused an increase in cirrus cover by a few percent regionally. This was shown by long-term ISCCP data trends (Zerefos et al.; in particular over continental USA, and the North Atlantic flight corridor) and by direct correlation between METEOSAT cirrus and aviation data (Mannstein; over Europe). The trends are not fully correlated with traffic everywhere. Cirrus cover variations due to annual variability or trends in UT humidity partially mask the effect of aviation.

With respect to the quantitative RF resulting from contrail cirrus, several estimates are available: From ISCCP trend analysis, Minnis et al. (2001) conclude a „spreading factor“ of 3.9. Zerefos et al. do not quantify this spreading factor but the derived cirrus trends are very similar compared to Minnis et al. (2001).

Minnis et al. (2003) conclude, that the RF from both linear contrails and the resulting contrail-generated cirrus clouds would be 15.3 mW m^{-2} . Within the project TRADEOFF (Isaksen et al.), this contribution was estimated far larger: 60 to 100 mW m^{-2} . Mannstein finds that the change in cirrus cover over Europe is 10 times larger than the cover by line-shaped contrails and concludes that the RF would be 10 times larger for the same optical properties, or even larger if contrail cirrus is optically thicker than line-shaped contrails; He concludes an RF of 30 - 90 mW m^{-2} , using the 3 - 9 mW m^{-2} range for line-shaped contrails.

The conference saw the first model results presented for soot impact on cirrus formation (Hendricks, Penner). The results show that the effects are potentially of important magnitude but the magnitude is not yet sufficiently known for a reliable assessment. Even the sign is uncertain: It appears that additional soot may reduce the number of ice particles forming and hence reduce their optical depth and the induced RF.

A contrail analysis has been performed with meteorology computed for present and future climate from a global circulation model. The results indicate that for the same amount of traffic, the line-shaped contrail cover would be smaller in a future climate because of a warmer upper troposphere.

Travis et al. (2002b) claim observable changes in the daily temperature range (DTR) due to reduced contrails in the three days period of 11-14 Sept. 2001, when air traffic over parts of the USA was reduced. They report that the DTR was 1 K above the 30-year average for the three days grounding period, adding evidence that jet aircraft do have an impact on the radiation budget over the US. However the DTR in 1982 was also nearly 1 K above the average and certainly for other reasons (Travis et al., 2002a). Hence, the statistical significance of the data is too weak to justify a strong conclusion.

6 OPEN ISSUES

6.1 *Nitrogen Oxides (NO_x)*

Although the scientific understanding of the processes and the quality of chemical transport models (CTMs) has increased considerably since IPCC (1999), the quantification of the impact of NO_x from aviation on ozone and methane is still very uncertain. Errors of the order of a factor of two are still likely to occur in present assessment studies. The uncertainties are due to errors in representation of transport (convective transports in the troposphere, transport near and across the tropopause, washout by rain etc.), cloud physics (cirrus and others), horizontal and vertical distribution of lightning NO_x sources (which may be improved in future studies using data from the projects MOZAIC, CARIBIC, TROCCINOX, CRYSTAL-FACE etc.), emissions at the surface, treatment of boundary layer chemistry and transport, climate/chemistry interaction, coupling to ocean and biosphere, and (to the authors opinion mainly) insufficient numerical resolution.

A recent study by Birner et al. (2002) shows that a stably stratified inversion forms just above the tropopause at scales of a few hundred meters. Hence, CTMs need to have 100 m vertical resolution (and a comparable resolution horizontally) in order to resolve the transport near the tropopause correctly. Findings of CTMs with various resolution performed so far do show little impact of resolution. However such studies remain inconclusive since they do not resolve important small scale structures such as the inversion near the tropopause. It is suggested to put far more emphasis on developing numerical schemes with high resolution. This should include a combination of homogeneously refined grids and nesting near the tropopause. The emphasis on resolution does not mean that other transport processes are unimportant such as vertical mixing in deep convection. Models dealing with supersonic aviation should include the whole stratosphere in order to represent the age of air masses in the stratosphere correctly.

It is suggested to perform a special workshop (perhaps within the coming ACCENT network of excellence funded by the EC) to develop a long-term model development strategy. At the end one should have a few very good CTMs and GCMs.

A long-term strategy for experiments in this field is also needed. It is recommended to enhance cooperation between modelers and experimenters. It was pointed out that the future of MOZAIC is in danger. Once the instruments are demounted from the present MOZIAC aircraft, a continuation will be difficult because of required certification. The data available from many experiments (such as NOXAR and GOME) show differences which are in part due to inter-annual variability, which is hard to detect from short time measurements. Therefore, the use of the many years of MOZAIC data is important.

6.2 *Aerosols and Contrails*

Aviation impact on climate may be largest via cirrus changes. The quantification of this impact has been advanced but the state of scientific understanding is still poor. The direct and indirect effects of aviation on cirrus are still not understood sufficiently for reliable quantification. Observational evidence for the direct effect is good, for the indirect effect it is still poor. Soot appears to be the most important aviation aerosol impacting cirrus formation, however models are still in an early development stage and atmospheric observations on soot impact on cirrus are few. In particular the fate of (aging) soot after emission has not yet been determined experimentally.

A prerequisite for assessments of the impact of aerosols and contrails on cirrus is a better understanding of cirrus formation. Correct modeling of the relative humidity and cirrus formation requires better information on vertical motions in the upper troposphere, distribution and freezing properties of heterogeneous ice nuclei, and physical parameterizations of subgrid-scale processes. For correct modeling of the occurrence of CCNs one would also need better knowledge of the distribution of condensable gases such as H₂SO₄.

As a new topic it was suggested to study the impact of aircraft emissions on the hydrological cycle. Changes in sedimentation and precipitation may be very important for climate and may be affected by cirrus changes due to aviation. Precipitation is one of the most difficult subject of meteorology. It needs long-term efforts to account for aircraft impact on precipitation. A further new topic of potential importance, the impact of cosmic rays was mentioned, see Eichkorn et al. (2002) and the editorial in *Science*, 298, of 20 Dec. 2002.

6.3 Mitigation

The potential impacts of different fuels, different engines, high speed transport, other flight levels or other flight routing on the aviation impact has still not be finally understood. Mitigation effects studied at this conference included cryoplanes (driven by liquid hydrogen, LH2, instead of kerosene) and changes in flight altitudes. LH2 fuel may be a viable alternative to kerosene in terms of climate impact if LH2 can be produced safely and with low climate impact. Reduced flight altitudes reduce the NO_x impact on ozone (and on methane) and may reduce the occurrence of line-shaped contrails. Whether this justifies a pledge for lower flight altitudes remains open. A reduction in flight levels would increase the emissions of CO₂ and has several negative impacts on flight endurance, air traffic management, and convenience of the passengers (e.g. due to increased turbulence and enlarged travel duration). The impact of changes in flight altitudes in cirrus formation is unknown. Also the impact on methane is not yet reliably determined.

The studies presented are necessary steps in developing environmentally sustainable aviation with growing air traffic. However, it may be that the mitigation effects are small compared to economic implications and the studies are not yet reliable enough for drastic changes in aviation procedures. It may turn out that the best strategy is to fly just above the tropopause in the dry lower stratosphere (where contrails remain short-lived, where NO_x impact on O₃ is small, where aircraft operate efficiently, and where turbulence levels are small). One may also consider to adjust the flight altitudes to the actual meteorology, e.g., to avoid contrails by avoiding flights in air masses with large relative humidity (above ice saturation).

7 CONCLUSIONS

In spite of considerable progress made, more research is needed to better understand both atmospheric and combustion science with respect to aviation impact on the global atmosphere. The topic of cirrus changes due to spreading contrails and soot emissions was at the center of the present conference, but the level of scientific understanding of this topic is still poor. It is recommended to initiate an amendment to the IPCC assessment which includes also the assessments of other traffic modes (such as by cars, trains, ships etc).

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