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Atmospheric Chemistry and Physics Discussions

TRADEOFFs in climate effects through aircraft routing: forcing due to radiatively active gases

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Abstract

We have estimated impacts of alternative aviation routings on the radiative forcing. Changes in ozone and OH have been estimated in four Chemistry Transport Models (CTMs) participating in the TRADEOFF project. Radiative forcings due to ozone and methane have been calculated accordingly. In addition radiative forcing due to CO_2 is estimated based on fuel consumption. Three alternative routing cases are investigated; one scenario assuming additional polar routes and two scenarios assuming aircraft cruising at higher (+2000 ft) and lower (–6000 ft) altitudes. Results from the base case in year 2000 are included as a reference. Taking first a steady state backward looking approach, adding the changes in the forcing from ozone, CO_2 and CH_4, the ranges of the models used in this work are –0.8 to –1.8 and 0.3 to 0.6 mWm^{-2} in the lower (–6000 ft) and higher (+2000 ft) cruise levels, respectively. In relative terms, flying 6000 ft lower reduces the forcing by 5–10% compared to the current flight pattern, whereas flying higher, while saving fuel and presumably flying time, increases the forcing by about 2–3%. Taking next a forward looking approach we have estimated the integrated forcing (mWm^{-2} yr) over 20 and 100 years time horizons. The relative contributions from each of the three climate gases are somewhat different from the backward looking approach. The differences are moderate adopting 100 year time horizon, whereas under the 20 year horizon CO_2 naturally becomes less important relatively. Thus the forcing agents impact climate differently on various time scales. Also, we have found significant differences between the models for ozone and methane. We conclude that we are not yet at a point where we can include non-CO_2 effects of aviation in emission trading schemes. Nevertheless, the rerouting cases that have been studied here yield relatively small changes in the radiative forcing due to the radiatively active gases.

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1 Introduction

Aircraft are known to yield impacts on climate in several ways, most significantly through emissions of gases that directly or indirectly impacts the levels of radiatively active gases, and through formation of condensation trails (contrails) and cirrus clouds. Substantial effort has been made to quantify radiative forcings due to all these mechanisms (see e.g. IPCC, 1999; Sausen et al., 2005). Investigation and assessment of ways to reduce environmentally negative impacts, including contributions to climate change, have taken various paths. First, there have been several propositions to technological solutions of the problems (Rogers et al., 2002), e.g. by altering aircraft design and configurations (Green, 2003; 2005; Akerman, 2005), or by using alternative fuel, for example liquid hydrogen (Marquart et al., 2001; Gauss et al., 2003; Svensson et al., 2004).

Second, various changes in operational practice have been proposed. In general, climate effects of aircraft are sensitive to where and when emissions take place, and thus a few attempts have been made to break climate impacts down e.g. to certain parts of the year or of the day (Myhre and Stordal, 2001; Stuber et al., 2006). However, regarding changes in operations a main emphasis has been on studies of changing cruise levels. Formation of contrails depends on temperature and moisture of the ambient air. Thus aircraft cruise altitude is a main factor in determining contrail formation (e.g. Sausen et al., 1996; Schumann, 2005). The same is true for the transition of contrails into cirrus clouds (Mannstein et al., 2005). These effects have been estimated in recent model experiments (Williams et al., 2002; Fichter at al., 2005).

Aircraft emissions of NO_x have a chemical impact on two radiatively active gases, namely ozone and methane (e.g. Grewe et al., 2002a, b; Dessens and Simon, 2002; Liu et al., 2003; Stevenson et al., 2004). It is well known that the atmospheric chemistry impacting ozone and OH and thus methane depends on location (altitude as well as geographical location) and time (of the day and of the year). Further, ozone is (unlike methane) not long lived enough to be well mixed in the troposphere, making the ozone

distribution even more sensitive to the location and time of aircraft emissions. Consequently, e.g. the altitude of aircraft NO_x emissions impacts the chemical effects on both ozone and methane (Grewe et al., 2002c; Williams et al., 2003), whereas in the case of ozone there is an additional dependence on the altitude distribution of ozone itself (Hansen et al., 1997; Forster and Shine, 1997; IPCC, 2001). The vertical distribution is important in defining the radiative impacts of ozone changes. Changes in the vertical routing patterns can therefore potentially be used to minimize climate impacts of aircraft traffic. Likewise, changes in geographical flight patterns will influence the impacts on ozone and methane. It has recently been suggested to include aviation emission into trading schemes. However, Forster et al. (2006) conclude that it is yet too early as the issue is not sufficiently investigated.

In this paper we study impacts of alternative routings, namely increasing or decreasing cruise altitudes of aircraft as well as making more extensive use of polar routing. In the EU FP5 research project TRADEOFF, several groups worked on estimates of the radiative forcings from aviation. Some main results from the project were summarized in Sausen et al. (2005). For this paper four Chemistry Transport Models (CTMs) and Climate-Chemistry Models (CCMs) have been used in combination with three radiative transfer models to estimate the direct forcing due to ozone. Chemical impacts on OH have also been estimated by the CTM/CCMs. The OH perturbations have been used to derive changes in methane, and a simple analytical relation (IPCC, 2001) has been used to derive impacts on the radiative forcing due to methane change. Alternative routings may also imply changes in the fuel use and thus emissions of CO_2. This has also been taken into account in this work in terms of changes in radiative forcings, again using an analytical relation (IPCC, 2001).

2 Models

In this work we have estimated aircraft-induced OH and O_3 changes. The perturbations to the concentrations of these species resulting from aviation NO_x emissions were

calculated with four Chemical Transport Models (CTMs) and Climate-Chemistry Models (CCMs). The four models have been evaluated by Brunner et al. (2003, 2005). The main model characteristics are described in the following. The three first models have included also calculations of RF due to ozone, whereas the fourth model estimated changes in ozone and OH concentrations only.

2.1 Oslo CTM2

The Oslo CTM2 model is a 3-D chemical transport model driven by ECMWF meteorological data and extending from the ground to 10 hPa in 40 vertical layers. The horizontal resolution can be varied, but for this study it was set to T21 (~5.6°×5.6°). Advection applies the Second Order Moment scheme of Prather (1986), while convection is based on the Tiedtke (1989) mass flux scheme. Transport in the boundary layer is treated according to the Holtslag K-profile method (Holtslag et al., 1990), and the calculation of dry deposition follows Wesely (1989). Surface emissions are taken from the EDGAR data base (Olivier et al., 1999) for anthropogenic, and from Mueller (1992) for natural emissions. Lightning emissions of NO_x are parameterized based on Price et al. (1997a, b) and scaled to 5 Tg(N)/year. The model calculates the distribution of 98 chemical compounds relevant for tropospheric and stratospheric chemistry applying two comprehensive chemistry modules, one for the troposphere (Berntsen and Isaksen, 1997a, 1999) and one for the stratosphere (Rummukainen et al., 1999), which both use the QSSA numerical solver (Hesstvedt et al., 1978). Photo-dissociation rates are calculated by the Fast-J module (Wild et al., 2000). The model was evaluated recently by Isaksen et al. (2005) and Brunner et al. (2003, 2005). A procedure to include small scale effects on formation of ozone from NO_x emissions has been included (Kraabøl et al., 2002). In general, this reduced the NO_x increase and thus the ozone formation due to aircraft, as will be discussed later.

The radiative transfer calculations are calculated by a separate model using different schemes for longwave and shortwave radiation (Berntsen et al., 1997b; Myhre et al., 2000), which have been used in several studies of radiative forcing due to ozone

changes (e.g. Gauss et al., 2006). The meteorological data used in the radiative transfer calculations are consistent with the Oslo CTM2 simulations. However, the calculations are performed with monthly mean data.

2.2 LMDz/INCA GCM

LMDz (version 3.3) is a GCM developed initially for climate studies (Sadourny and Laval, 1984). The model has been adapted in order to simulate the transport of trace species and is coupled on-line to the chemistry-aerosols model INCA (INteraction with Chemistry and Aerosols). The present version of the model has 19 hybrid levels from the surface to 3 hPa and a horizontal resolution of 2.5 degrees in latitude and 3.75 degrees in longitude. The large-scale advection of tracers is performed using a finite volume transport scheme (Van Leer, 1997) as described in Hourdin and Armengaud (1999). Convective transport is simulated using a massflux scheme (Tiedtke, 1989). The planetary boundary layer scheme is based on a second-order closure approximation. The current version of the model uses a CH_4-NO_x-CO-O_3 chemical scheme representative of the background chemistry of the atmosphere and including 19 photochemical reactions and 66 chemical reactions. INCA calculates on-line the time evolution of 33 chemical species and tracers with a time step of 30 min. In the present version of the model, the feedback of the chemistry on the radiation is not taken into account. A zonally and monthly ozone climatology is prescribed above the tropopause based on Li and Shine (1995). An interactive lightning NO_x emission scheme is used in the model (Jourdain and Hauglustaine, 2001). While the LMDz GCM wind fields can be relaxed towards ECMWF reanalysis, this model feature is not activated in the version of LMDz used in this study and the GCM winds fields, temperature, humidity and cloudiness are used to drive the transport and chemistry of the chemical species. A detailed description and evaluation of the model is provided by Hauglustaine et al. (2004).

The ozone radiative forcings at the tropopause are calculated with an off-line version of the LMDz GCM radiative transfer model. The model is based on the European Centre for Medium-Range Weather Forecasts (ECMWF): a refined version of the scheme

developed by Fouquart and Bonnel (1980) in the solar part of the spectrum and by Morcrette (1991) in the thermal infrared. The forcings are calculated on a monthly mean basis using the temperature, water vapour, cloud distributions and optical properties, surface albedo, and ozone fields stored from a previous GCM simulation and read from pre-established history files. The fixed-dynamical heating concept is applied to the calculations.

2.3 ULAQ CTM

ULAQ model from the University of L'Aquila is a low-resolution three-dimensional aerosol-chemistry-transport model that uses a 10×22.5 degree resolution in latitude-longitude and 26 log-pressure levels, from the ground to about 0.04 hPa, with an approximate resolution of 2.84 km. Dynamical fields are taken from the output of a spectral general circulation climate model (Pitari et al., 2002). The chemical module contains the most important photolytic, gas phase and heterogeneous reactions relevant for stratospheric chemistry, including O_x, HO_x, NO_y, ClO_x, BrO_x, CHO_x and SO_x families. Sulphur precursors in the model are SO_2, OCS, DMS, H_2S, and CS_2, with SO_2 being the most important species for the sulphur budget into the lower stratosphere, and OCS for the middle stratosphere. SO_2 comes from both natural sources (volcanoes, oceans, biomass burning) and anthropogenic activities (fossil fuel burning, in situ emissions from aircraft) and is efficiently transported from the boundary layer up to the tropical tropopause layer via deep convection (Pitari et al., 2002). The model also includes the major components of tropospheric and stratospheric aerosols (sulphate, carbonaceous, dust, sea salt).

The ULAQ-GCM has been used to calculate the different components of the radiative forcing. O_3, H_2O, BC and sulphate fields are taken from the ULAQ-CTM simulations. The infrared contribution to the cooling rate by the 0_3 9.6-μm band has been evaluated following the assumption of "cooling to space" (Andrews et al., 1987). O_3 absorption in the UV and visible wavelengths is calculated from tabulated solar fluxes and cross sections.

2.4 TOMCAT CTM

is a global three-dimensional chemistry transport model (Law et al., 1998, 2000) and in its configuration used for this study the model has recently undergone a rigorous validation with airborne in-situ observations (Brunner et al., 2003, 2005). The model domain extends from the surface to 10 hPa with 31 hybrid pressure levels and the horizontal resolution is 5.6 by 5.6 degrees. Using meteorological forcing from the ECMWF the model uses the Prather (1986) advection scheme with conservation of second-order moments and a dynamical time step of 30 min. Moist convective transport of tracers is parameterised by the Tiedtke (1989) mass flux scheme. Lightning NO_x emissions are coupled to the convection scheme (Price and Rind, 1992; Stockwell et al., 1999). The model also includes the Holtslag and Boville (1993) non-local vertical diffusion scheme, based on the NCAR Community Climate Model Version 2 (CCM2), which calculates explicitly the height of the planetary boundary layer (Wang et al., 1999) TOMCAT uses the ASAD chemistry package (Carver et al., 1997) which describes gas phase CH_4-CO-NMHC-NO_x chemistry, using a chemical time step of 15 minutes. In 28 photolytic, 89 bimolecular and 15 termolecular reactions the TOMCAT model considers 47 chemical species, of which 27 are advected. Rate coefficients are taken from Atkinson et al. (1997) and DeMore et al. (1997), photolysis rates are calculated off-line in the Cambridge 2-D Model (Law and Pyle, 1993). The simplified treatment of NMHCs considers the degradation of ethane and propane. TOMCAT also takes account of loss through dry deposition at the surface, moreover a wet scavenging scheme based on the occurrence of convective and large-scale rainfall (Giannakopoulos et al., 1999) is included.

3 Assumptions

3.1 Base case fuel burn and NO_x emissions

In the model simulation performed for this work we focus on effects of aircraft in year 2000 and various perturbation scenarios for the same year. In the analysis of the climate impact we also consider the long term effects on radiative forcing (cf. Sect. 3.3). The cases and model experiments are summarized in Table 1. Aircraft emissions are based on 1991/92 aircraft movements, corrected by ICAO statistics through to 2000 and converted into emissions, fuel burn and distance travelled (Stordal et al., 2005; Sausen et al., 2005). In the cases used in our study military aircraft are neglected (Gauss et al., 2006), reducing fuel burn by approximately 10%. This must be kept in mind when changes in chemistry and radiative forcing are discussed. However, in the perturbation cases where we investigate impacts of alternative routings it is fair to assume that the civil traffic could be more easily rerouted than the military one. The global NO_x emission amounts to 0.594 Tg (N) and the total fuel burn is 152 Tg per year. We have not scaled our radiative forcings by a factor of 1.15 as has been done by other investigators (e.g. IPCC, 1999) in order to account for extra fuel burn due to non-perfect routing, sub-optimal cruise altitude, holding cycles, etc.

3.2 Alternative routing cases

A main emphasis in this work is on impacts of alternative routing. Polar routes are used increasingly on long distance intercontinental flights. As the chemistry is quite different in polar regions compared to middle latitudes we investigate the impact of an additional fraction of polar routes. When implementing additional polar routes we have kept the total global emissions fixed in order to isolate the impact of their redistribution. Thus we assume that polar routes are added at the expense of non-polar routes so that the amount of fuel burnt is not affected (Table 1). Further, flying at different altitudes will potentially alter the climate impact of aircraft. Such effects clearly need to be in-

vestigated in order to understand whether and how alternative routing may be used to reduce the climate impact of air traffic. Also the aviation industry will consider options to reduce the fuel consumption. Operating at higher flight levels is an option working in this direction.

We have chosen to focus on three different alternative routing scenarios defined in the TRADEOFF project, namely one scenario assuming additional polar routes and two scenarios assuming aircraft cruising at higher (+2000 ft) and lower (–6000 ft) altitudes. Notice that in the case of altered cruise altitudes fuel burn as well as NO_x emission indices will be modified (see details in Table 1). The calculated impacts on the chemical changes due to alternative routings are partly due to changes in emission totals, which are listed in Table 1, but more due to the fact that emissions take place at different locations compared to the base case (Gauss et al., 2006).

3.3 Forcing estimates

The radiative forcing of the CH_4 change is estimated from a change in CH_4 lifetime resulting from the OH change simulated with the CTMs. In estimating the methane forcing we have used the model derived reductions in the methane lifetime, which has been multiplied with a factor 1.4 to take into account feedback mechanisms (Berntsen et al., 2004, 2005; Derwent et al., 1999; Isaksen et al., 1999; Prather et al., 2001). The inferred change in global tropospheric methane has been used to estimate the RF adopting the analytical relation between methane and its RF given in IPCC (2001, Chapter 6). The CTM simulations and further calculations with radiative transfer models give the RF for the short-term perturbation of ozone. However, as described by Prather (1996) and Wild and Prather (2000), the long term (primary mode) change in methane (which is not captured directly in the CTMs due to the short integration time) will also cause perturbation in ozone with a timescale corresponding to the perturbation lifetime of methane. Here we follow the procedure described in Appendix 2 of Berntsen et al. (2005) to estimate the radiative forcing of this effect.

The RF from aviation CO_2 has been derived based on EDGAR emission data (Olivier

and Berdowski, 2001) assuming a decay function for CO_2 taken from IPCC (1995); $CO_2(t) = CO_2(0) * (0.30036\exp(-t/6.993) + 0.34278\exp(-t/71.109) + 0.35686\exp(-t/815.727)$. We have applied the analytical relation between mixing ratio change and RF in IPCC (2001, Chapter 6, 15.48 mWm^{-2}/ppm). In the base case for year 2000 used in this work this forcing is 21.7 mWm^{-2}. This is lower than the 25 mWm^{-2} given in Sausen et al. (2005) as military traffic and the upscaling to account for non-perfect routing have been neglected here. Whereas the fuel burn grew somewhat faster from 1992 to 2000 than assumed by IPCC (1999) a slightly smaller RF per unit CO_2 increase is assumed now (IPCC, 2001 vs. IPCC, 1999, Myhre et al., 1998).

Assessing the effects of alternative routing can be done in several ways. First we take a simple approach by looking backward and assuming that all flights in the past have been according to the alternative routings. Thus we are estimating the accumulated effect of the various alternatives in the past. This is done by scaling the present CO_2 concentrations by the changes in fuel consumption and present CH_4 concentrations by the change in the methane lifetime.

Another approach is more useful in order to assess future impacts of alternative routing, namely to look forward and estimate the changes in time integrated radiative forcing over a time span when alternative routing may be assumed to be in effect. We have taken also this approach in this work by investigating future changes on time horizons of 20 and 100 years (used as time horizons in estimates of GWP by IPCC). We are assuming constant emissions and flight patterns over these time horizons. NO_x and ozone have relatively short lifetimes, and we assume that the forcing for ozone that we have calculated from the steady state experiments is obtained instantaneously and is sustained over the 20 and 100 year time horizons. For CO_2 and CH_4 we take into account the accumulated effect over the 20 and 100 years time periods due to the change in emissions in the first case and the change in the loss in the latter case. We have first estimated the time evolution in the global average mixing ratios (in ppm) of CO_2 and CH_4 due to aircraft emissions in the base case and the alternative routing cases. In these calculations we have assumed the same decay function for pulses

of CO_2 as given above. Second, we have integrated the changes in mixing ratios (deviation from the case without aircraft in the base case, deviations from the base case in the alternative routing cases; in ppm yr). Finally, we have multiplied with the specific radiative forcing (in mWm^{-2}/ppm; as described above for CH_4 and CO_2), resulting in an integrated forcing over the 20 and 100 year time periods (in Wm^{-2} yr).

4 Results

4.1 Base case 2000

Results for the base case in year 2000 are discussed in more detail elsewhere (Sausen et al., 2005; Gauss et al., 2006). We include only a brief presentation which is needed to put the results of the perturbation studies in perspective. The ozone changes due to NO_x emissions are largest at mid and high latitudes in the Northern Hemisphere (NH) (Fig. 1a). Maximum perturbations are modelled during late spring and early summer (see e.g. Gauss et al., 2006). Near the maximum aircraft traffic at mid latitudes in NH Oslo CTM2 estimates somewhat lower impact of aircraft than the LMDz/INCA and TOMCAT models, most likely due to the reduced effect from small scale effects, which reduces the impact on ozone by up to 20%. The latitudinal gradient in the ozone increase from mid to high latitudes in NH varies quite substantially between the models. The flights are predominantly in the stratosphere at high latitudes. Thus differences in stratosphere-troposphere exchange and meridional transport between the models yield large differences in impacts of NO_x emissions. The total amount of ozone added is in the range 0.31 to 0.45 DU globally (Table 2). Further, the NO_x emissions lead globally to increased OH concentrations and a reduced lifetime of methane. In the three models the lifetime change is in the range –0.7% to –1.6% (Table 3).

The RF from short term ozone perturbations is also largest at mid and high latitudes in the NH (Fig. 2). The time of the maximum is shifted somewhat towards the summer (not shown here, see e.g. Gauss et al., 2006), due to the higher elevation of the sun

effecting the shortwave component of the forcing. The global forcing is in the range 11 to 16 mWm^{-2} (mean 14 mWm^{-2}) in the three estimates made here (Table 4). Sausen et al. (2005) reported forcings due to ozone in the range 12 to 28 mWm^{-2} resulting from TRADEOFF, with an average value of 19 mWm^{-2} (scaled to 22 mWm^{-2}). As there are fewer models contributing to this work, the interval is somewhat narrower than in Sausen et al. (2005), and the mean value is somewhat lower as a lower traffic scenario (without military aircraft) has been assumed. Even the Sausen et al. (2005) RF is somewhat smaller than the IPCC-based estimate for 2000; however, in the light of the large confidence interval this difference is not significant. The long-term (primary mode, cf. Sect. 3.3) forcing due to ozone was not estimated by Sausen et al. (2005). For the base case, we estimate this RF to be between –6 and –3 mWm^{-2} (when the system has reached a new steady state).

The corresponding RF from aircraft-induced CH_4 loss is in the range –6 to –14 mWm^{-2} (mean –10 mWm^{-2}) based on the four estimates here (Table 5). In estimating the methane forcing we have used the reductions in the methane lifetime from Table 3, which has been up-scaled to take into account the feedback mechanism through OH changes (Sect. 3.3). Thereafter the inferred change in global tropospheric methane has been used to estimate the RF adopting an analytical expression. The methane RF given in Sausen et al. (2005) was similar, namely –9 mW/m^2 (scaled to –10 mW/m^2). Our results are lower than the IPCC-based estimate, but still within the confidence interval of IPCC (1999).

As mentioned in Sect. 3 the forcing due to CO_2 in the base case is 21.7 mWm^{-2} (Table 6). This is somewhat larger in magnitude than the ozone and methane forcings, working in the same direction (heating) as the ozone forcing but opposite to the methane forcing (cooling).

4.2 Additional polar routes

Two models have been run for this case. In both models there is less ozone production due to aircraft at middle latitudes in the NH, as some flights are moved from these to

higher latitudes. However, only in one of the models (Oslo CTM2) there is a partly compensating increased ozone production at the high latitudes (Fig. 1b) in the yearly average. The other model (ULAQ) has a coarser spatial resolution that most probably explains the model difference. Thus there is a wide range in the change in global total ozone; –0.0089 to –0.0467 DU (Table 2). In Fig. 3 we see that in the polar region both models estimate a strong seasonal variation in ozone changes. Whereas the Oslo CTM2 model has only weak changes during the winter, the ULAQ model estimates ozone loss at that time of the year. On the other hand the expected ozone increase during the summer is much stronger in the Oslo CTM2 than in the ULAQ model.

The impact on radiative forcing due to ozone is quite similar, with reduced RF at middle latitudes in the NH in both models, and a partly compensating increase at high latitudes in one of the models (Fig. 2). The range of changes in net (short-term and primary mode) RF on a global scale is therefore also large, namely +0.06 to –1.15 mWm^{-2} (Tables 4 and 7). The seasonal variation at high latitudes depicts the same pattern as the changes in ozone (Fig. 3). The RF due to changes in methane is more similar in the two models (Table 5). It is significant in comparison with the forcing due to ozone and it works in the different direction (warming by methane vs cooling in the ozone case), namely in the range 0.73 to 0.99 mWm^{-2}. As we have assumed no change in fuel burn (Sect. 3.2) in this experiment CO_2 emission are the same as in the base case and there is no change in the RF due to CO_2 (Table 6).

4.3 Lower cruise altitudes

We investigate next the impact of lower cruise altitudes, and we use the TRADEOFF scenario where the flight levels are reduced by 6000 ft. Three models (Oslo CTM2, LMDz/INCA and TOMCAT) estimate a decrease in ozone (Table 2), especially at middle and high NH latitudes (Fig. 1). In these three models the ozone loss resulting from aircraft NOx emissions is reduced by –4 to –13% as a result of 6000 ft (approximately 1.8 km) reduced cruise altitudes. This is a somewhat weaker effect than the 10% reduction estimated by Grewe et al. (2002c) for a 1 km lower cruise altitude. In

LMDz/INCA the ozone reductions are largest at high latitudes, probably as a result of a quite efficient meridional transport in this model. The three other models have largest changes at middle latitudes, near the maximum of the impact of aircraft emissions of NO_x on ozone. Like in LMDz/INCA the ozone change is negative in Oslo CTM2 and TOMCAT as expected, due to a shorter lifetime for NO_x as well as ozone. However, it is positive in ULAQ, which is more difficult to explain. Figure 4a shows that in Oslo CTM2 there is an increase in ozone at high latitudes during the winter and a decrease in the summer. In LMDz/INCA there is an ozone decrease throughout the year with a maximum decrease during the summer which is much stronger than in Oslo CTM2. The ULAQ model estimates increases in ozone, particularly strong at middle NH latitudes (Fig. 1), prevailing throughout the year (Fig. 4). At high latitudes this model estimates negative ozone changes only for the spring and early summer seasons. As in the base case the differences between the models are largest at high latitudes, as discussed in Sect. 4.1. The radiative forcing due to ozone follows patterns which parallel those of the changes in ozone in each of the three models (Figs. 2 and 4). The range of global and seasonal averaged forcings due to the net ozone changes in this case is –1.88 to +0.14 mWm^{-2} (Tables 4 and 7).

Although the ozone changes are both positive and negative in the three models, the changes in OH and thus methane are in the same direction in all models. However, the range between the models is large, namely –0.15 to –3.17 mWm^{-2} (Table 5). In this scenario the magnitude of the forcing due to CO_2 related to increased fuel burn is 1.27 mWm^{-2} (Table 6).

4.4 Higher cruise altitudes

Next we investigate the impact of higher cruise altitudes. In this case the levels are increased by 2000 ft. Consequently, one would expect a somewhat weaker impact than in the previous case where the magnitude of altitude change was three times larger (6000 ft). The ozone perturbations in the three models that gave ozone decrease in the previous case are now positive. The signal is somewhat lower, but stronger than 1/3 of

the signal in the reduced cruise altitude case (Table 2). The latitudinal patterns in the changes are similar (Fig. 1), except for the model that predicted ozone decrease in the previous case, as this model also gives positive ozone perturbation in this case. The ozone RF results are quite parallel to the results for ozone itself (Fig. 2). The range of net RF due to ozone is +0.51 to +0.87 mWm^{-2} (Tables 4 and 7).

Based on the results for changes in RF from methane it seems like currently aircraft fly at a level with near a maximum impact on methane RF, as two models predict reductions in the RF for lower as well as higher cruise altitudes, and the remaining two models estimate only very weak positive changes in the RF in the higher cruise altitude case. The range of the methane forcing is –0.48 to +0.09 mWm^{-2} (Table 5). The magnitude of the forcing due to CO_2 in this scenario has switched sign compared to the reduced altitude case, but the absolute magnitude is reduced by much more than a factor 3, as the forcing is –0.11 mWm^{-2} (Table 6).

5 Discussion and summary

The TRADEOFF project has provided an opportunity to study climate impacts of alternative aircraft routings. In this work we focus only on radiative forcing due to greenhouse gases, namely ozone, methane and CO_2. As a reference we have estimated the forcing due the three greenhouse gases due to aircraft traffic in year 2000. The data that we have used exclude military aircraft. The forcings from the three gases are well within the confidence intervals of IPCC (1999) and consistent with the TRADEOFF summary paper of Sausen et al. (2005). The forcings due to ozone (net change), methane and CO_2 are 8.2 to 14, –6.3 to –14, and 22 mWm^{-2}, respectively. Adding the numbers model by model (for Oslo-CTM2, LMDz/INCA and ULAQ), the range of the total forcing from all the three gases is 21 to 29 mWm^{-2}.

As discussed in Sect. 3.3 we are taking two different approaches when assessing the impact of the alternative routings investigated here; a backward looking and a forward looking approach. Taking first the backward looking approach, adding the changes in

the forcing from ozone, CO_2 and CH_4, the ranges of the models used in this work are -0.8 to –1.8 and 0.3 to 0.6 mWm^{-2} in the lower (–6000 ft) and higher (+2000 ft) cruise levels, respectively. These numbers are relatively moderate compared to the forcing in the base case. In relative terms, flying 6000 ft lower reduces the forcing by 5–10%, whereas flying higher, while saving fuel and presumably flying time, increases the forcing by about 2–3%. However, the uncertainty is considerable in these estimates. One important source of uncertainty, in particular at high latitudes, is differences in transport (most importantly stratosphere-troposphere exchange and meridional circulation) between models, especially since aircraft emissions take place partly in the troposphere (mid latitudes) and in the stratosphere (high latitudes), yielding significant differences between the models. The differences are even larger for the additional polar routes scenario. Unfortunately, only two models have run this case, and they give different signs in the change in the radiative forcing. The range of the forcing in this case is –0.4 to + 1.1 mWm^{-2}, which amounts to roughly a 2–4% impact, positive or negative, compared to the base case.

Taking next the forward looking approach we have estimated the integrated forcing (mWm^{-2} yr) over 20 and 100 years time horizons, as explained above. The results are summarized in Table 8. Basis for the results are averages in methane life times between four models (Table 3) and ozone forcings from three models (short term plus primary mode, Tables 4 and 7). We have made projections for the base case and the lower and higher cruise altitude cases, but not for the additional polar routing cases where only two models have provided data and the discrepancy between the models is large. In Table 8 the results are presented in terms of integrated radiative forcing over 20 and 100 years time horizon (in mWm^{-2} yr) and also relative to the contributions from CO_2 (for each of the two time horizons separately, in %) to ease the assessment of the relative contributions of each of the contributions.

In the forward looking approach the relative contributions are somewhat different from the backward looking approach. The differences are moderate adopting 100 year time horizon, whereas under the 20 year horizon CO_2 naturally becomes less impor-

tant relatively. The situation regarding the relative contribution for CO_2 is similar in the alternative routing cases. The relative importance of O_3 vs CH_4 follows a similar pattern, with ozone being more important than methane (ozone heating, methane cooling) in the base case, most pronounced under the forward looking 20 year time horizon.

In the alternative routing cases the total forcing is highly dependent on the method that is used for evaluation, as the contributions from O_3, CH_4 and CO_2 vary in different ways and are comparable in magnitude, so that the net balance differs widely between the various cases. In the higher cruise altitude case the net forcing is positive in all analyses, but it varies from 3.5 to 1.3% increase in forcing (warming) compared to the base case under the forward looking 20 and 100 year time horizons, respectively. The corresponding increase under the backward looking approach is 1.8% from the base case. In the lower cruise altitude case the net forcing is negative (cooling) in all analyses, varying from –5.2 to –0.4% reduction compared to the base case under the forward looking 20 and 100 year time horizons, respectively. The corresponding change under the backward looking approach is –5.9% from the base case. As an example of how sensitive the balance between the individual effects is we can mention that if we neglect the primary mode contribution to the ozone RF, in the lower cruise altitude case the accumulated forcing taking the forward looking approach shifts from cooling under the 20 year to heating under the 100 year horizon. Thus, not only are the changes in the concentrations of ozone and methane uncertain, as demonstrated from the significant differences between the models, but also the forcing agents impact climate differently on various time scales. Thus it is important also to take time scales into account when alternative routings are to be assessed. Thus we agree with Forster et al. (2006) that we are not yet at a point where we can include non-CO_2 effects of aviation in emission trading schemes. Nevertheless, the rerouting cases that have been studied here yield relatively small changes in the radiative forcing due to the radiatively active gases.

It is worth noticing that the change in RF from contrails as a result of rerouting could be at least as large as from the gases. E.g. Fichter et al. (2005) found a reduction of

15% in RF from contrails for a 6000 ft lower cruise altitude. Using the IPCC (IPCC, 1999) and the TRADEOFF (Sausen et al., 2005) values for RF from contrails this reduction amounts to a change in the RF by –1.5 to –5 mWm^{-2} in comparison with the –0.8 to –1.8 mWm^{-2} found in this work for the radiatively active gases.

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Table 1. Summary of the model simulations and TRADEOFF aircraft emission scenarios used in this work. The scenarios are a subset of those used and further explained and investigated in Gauss et al. (2005).

Model run	Aircraft emission scenario used	Fuel burn Tg/year	Total nitrogen emission[1)] Tg(N)/year	E.I.(NO_x) fleet average [2)]
no_air	no aircraft	–	–	–
base	base case	152	0.594 (16.9%)	12.9
pol_norm	additional polar routes, normalized [3)]	152	0.594 (34.1%)	12.9
low_adj	lower cruise altitude (–6000 ft), changed fuel burn[3)]	161	0.620 (5.8%)	12.7
high_adj	higher cruise altitude (+2000 ft), changed fuel burn[3)]	151	0.604 (20.0%)	13.1

[1)] The fraction of aircraft emissions occurring in the stratosphere is given in parenthesis.
[2)] The NO_x emission index, E.I.(NO_x), is defined as grams of NO_x (as NO_2) emitted per kg of burnt fuel.
[3)] Changes in flight routing will in general imply changes in fuel burn. In the "adjusted fuel burn" cases this effect is taken into account, while the "normalized" scenario uses the same total fuel burn as in the base case.

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Table 2. Change in global ozone (DU) due to aircraft. Results are given for current (2000) conditions (base case) as well as three cases of changes in aircraft routing (34 DU=370 Tg).

Case	Difference	Oslo CTM2	LMDz/INCA	TOMCAT	ULAQ
Base case	base – no_air	+0.338	+0.445	+0.308	+0.328
Add polar routes	pol_norm – base	–0.0089			–0.0467
Lower cruise alt	low_adj – base	–0.0136	–0.0429	–0.0404	+0.0365
Higher cruise alt	high_adj – base	+0.0157	+0.0271	+0.0193	+0.0172

Table 3. As for Table 1, but for global methane lifetime (%). Feedback mechanisms are not taken into account in the numbers given in this table.

Case	Difference	Oslo CTM2	LMDz/INCA	TOMCAT	ULAQ	Average
Base case	base – no_air	–0.71	–1.31	–1.59	–0.69	–1.08
Add polar routes	pol_norm - base	+0.11			+0.08	
Lower cruise alt	low_adj – base	–0.15	–0.02	–0.09	–0.35	–0.15
Higher cruise alt	high_adj – base	+0.00	–0.05	–0.04	+0.01	–0.02

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Table 4. Global radiative forcing (mWm^{-2}) due to short-term increase of ozone from aircraft. Results are given for current aircraft (base case) as well as three cases of changes in aircraft routing.

Case	Difference	Oslo CTM2	LMDz/INCA	ULAQ	Average
Base case	base – no_air	+10.84	+15.92	+16.10	14.29
Add polar routes	pol_norm – base	–0.35		–1.45	
Lower cruise alt	low_adj – base	–1.21	–1.82	+1.45	–0.53
Higher cruise alt	high_adj – base	+0.68	+1.07	+ 0.47	+0.74

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Table 5. Global radiative forcing (mWm^{-2}) due to methane resulting from aircraft. Results are given for current aircraft (base case) as well as three cases of changes in aircraft routing. Results are based on changes in methane lifetime corrected for feedback mechanisms (see text for further details), and on an analytical relation between methane changes and the radiative forcing from IPCC (2001).

Case	Difference	Oslo CTM2	LMDz/INCA	TOMCAT	ULAQ	Average
Base case	base – no_air	–6.4	–11.9	–14.4	–6.3	–9.8
Add polar routes	pol_norm – base	+0.99			+0.73	
Lower cruise alt	low_adj – base	–1.34	–0.15	–0.84	–3.17	–1.38
Higher cruise alt	high_adj – base	+0.03	–0.48	–0.38	+0.09	–0.19

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Table 6. Global radiative forcing (mWm^{-2}) due to CO_2 resulting from aircraft. Results are given for current aircraft (base case) as well as three cases of changes in aircraft routing (see text for details).

Case	Difference	Forcing
Base case	base – no_air	21.7
Add polar routes	pol_norm – base	0.00
Lower cruise alt	low_adj – base	1.27
Higher cruise alt	high_adj – base	–0.11

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Table 7. Global radiative forcing (mWm^{-2}) due to O_3, CH_4 and CO_2 resulting from aircraft, summarising the results in Tables 3–5. Results are given as ranges (encompassing individual models) for current aircraft (base case) as well as three cases of changes in aircraft routing. The total effect is also given for each of there models individually.

Case	Difference	O_3 (Short-term)	O_3 (primary mode)	CH_4	CO_2	Total OsloCTM2,LMDz/INCA,ULAQ
Base case	base – no_air	+10.8 to +16.1	–2.6 to –6.0	–6.3 to –14.4	21.7	+23.5, +20.8, +28.9
Add polar routes	pol_norm – base	–0.35 to –1.45	+0.30 to +0.41	+0.73 to +0.99	0.00	+1.05, NA, –0.42
Lower cruise alt	low_adj – base	–1.82 to +1.45	–0.06 to –1.31	–0.15 to –3.17	1.27	–1.83, –0.76, –1.76
Higher cruise alt	high_adj – base	+0.47 to 1.07	–0.20 to +0.04	–0.48 to +0.09	–0.11	0.61, 0.28, 0.49

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Table 8a. Integrated global radiative forcing over a 20 year time horizon due to O_3 (short term plus primary mode), CH_4 and CO_2. Results are given for current aircraft (base case) as well as two cases of changes in aircraft routing and are given in mWm^{-2} yr (in per cent of the base case CO_2 contribution in parentheses).

Case	Difference	O_3	CH_4	CO_2	Total
Base case	base – no_air	+251 (144)	–82.8 (–47.6)	+174 (+100.0)	+342 (+197)
Lower cruise alt	low_adj – base	–17.3 (–10.0)	–11.7 (–6.7)	+11.1 (+6.4)	–17.9 (–10.3)
Higher cruise alt	high_adj – base	+14.3 (+8.3)	–1.6 (–0.9)	–0.9 (–0.5)	+11.8 (+6.8)

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Table 8b. As Table 8a, but for100 yr time horizon.

Case	Difference	O_3	CH_4	CO_2	Total
Base case	base – no_air	+1130 (+39.0)	–641 (–22.0)	+2920 (+100.0)	+3410 (+117.0)
Lower cruise alt	low_adj – base	–110 (–3.8)	–90.1 (–3.1)	+187 (+6.4)	–13.5 (–0.5)
Higher cruise alt	high_adj – base	+70.0 (+2.4)	–12.1 (–0.4)	–15.2 (–0.5)	+42.7 (+1.5)

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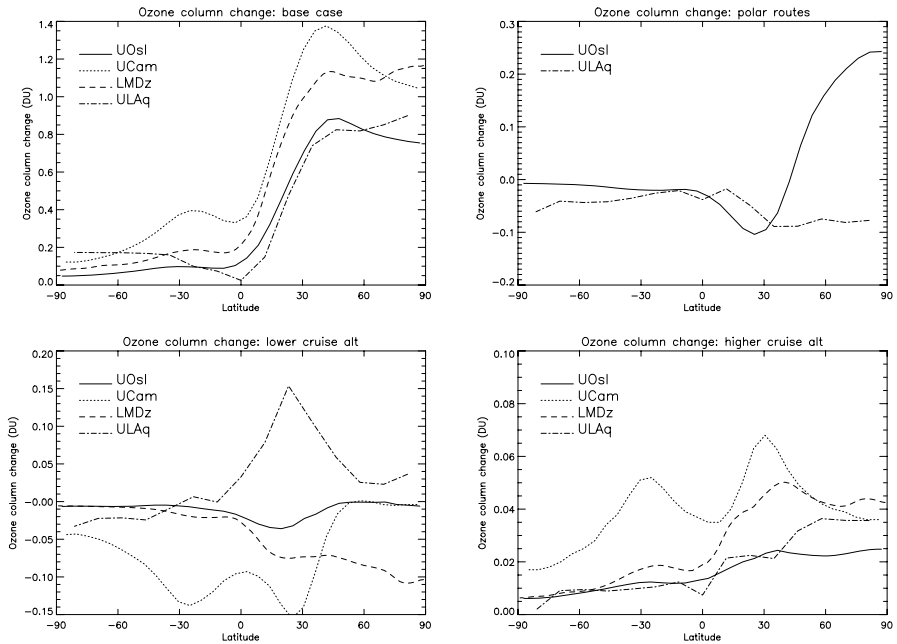

Fig. 1. Zonally and yearly averaged ozone column change (DU) due to aircraft as a function of latitude; upper left) base case, upper right) additional polar routes, lower left) lower cruise altitude, and lower right) higher cruise altitude.

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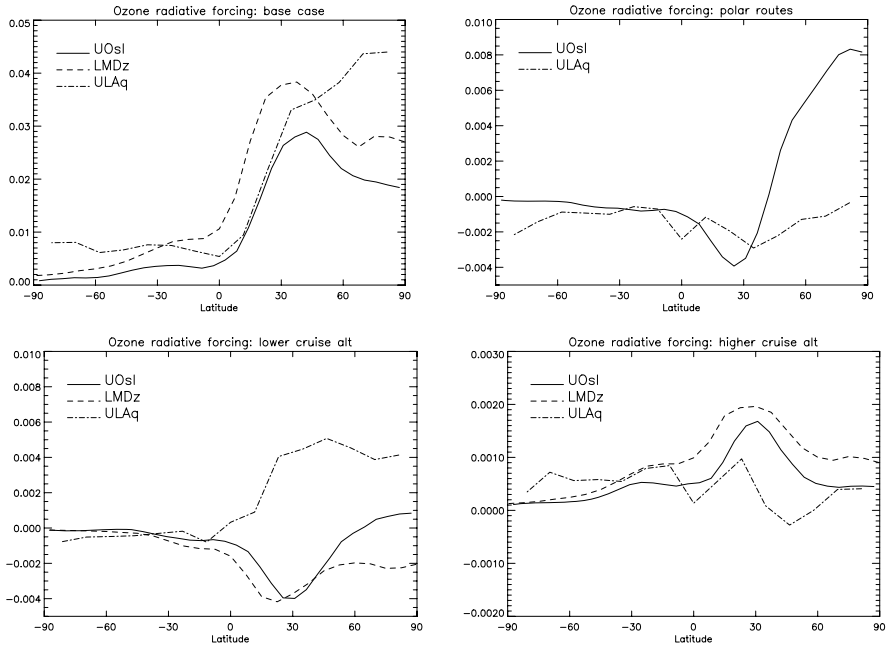

Fig. 2. Zonally and yearly averaged radiative forcing (Wm^{-2}) due ozone resulting from aircraft as a function of latitude; upper left) base case, upper right) additional polar routes, lower left) lower cruise altitude, and lower right) higher cruise altitude.

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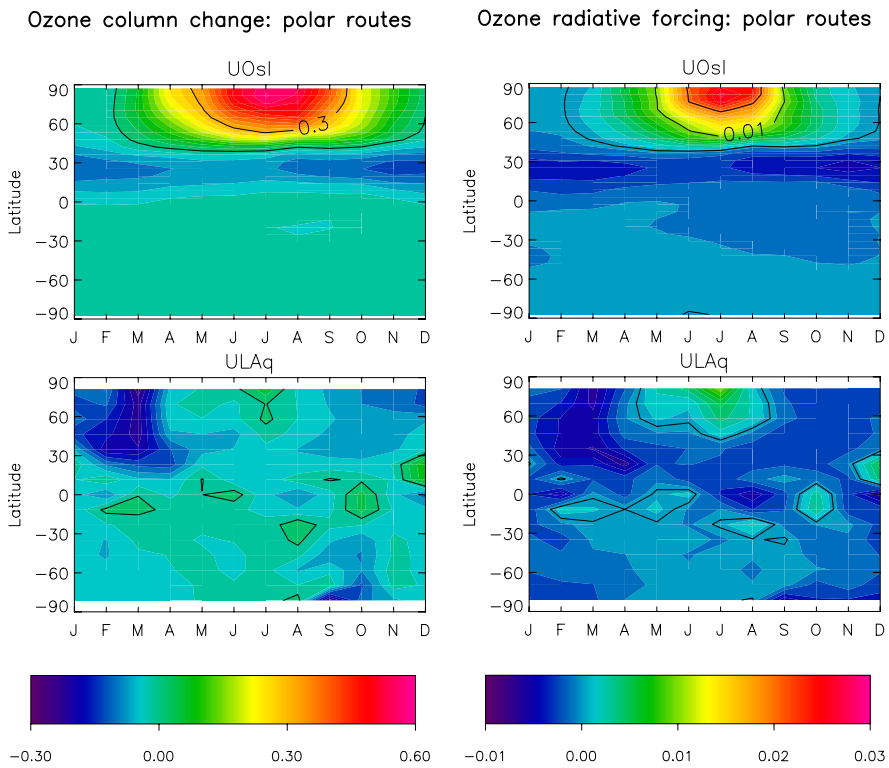

Fig. 3. Zonally averaged changes in (left) ozone column (DU) and (right) radiative forcing (Wm^{-2}) due ozone resulting from aircraft as a function of latitude and season in the case of additional polar routes.

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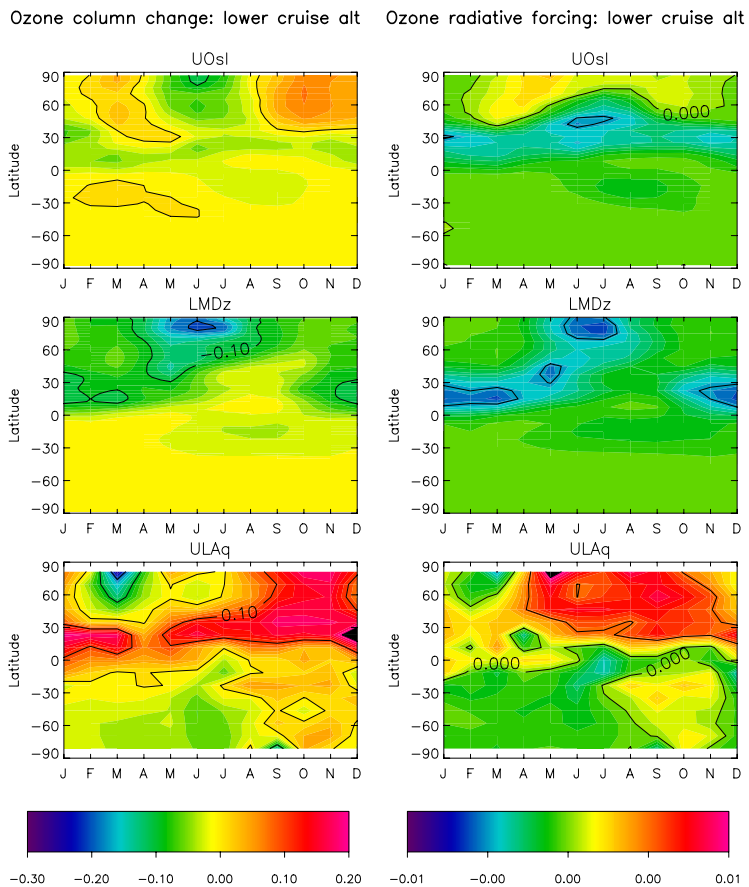

Fig. 4. Zonally averaged changes in (left) ozone column (DU) and (right) radiative forcing (Wm^{-2}) due ozone resulting from aircraft as a function of latitude and season in the case of lower cruise altitude.

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