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Global contrail radiative forcing and the impact of diurnal variations of air traffic

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Abstract

We combined high resolution aircraft flight data from the EU Fifth Framework Programme project AERO2k with analysis data from the ECMWF's integrated forecast system to calculate diurnally resolved 3-D contrail cover. Calibrating for the 1992 contrail cover in the Bakan area (eastern-Atlantic/western-Europe), we obtained a global, annual mean contrail cover due to persistent, line-shaped contrails of 0.04%. Adopting a contrail visible optical depth of 0.1, this contrail cover results in a global, annual mean radiative forcing of $2.0\,\mathrm{mW/m^2}$ for all-sky and $2.1\,\mathrm{mW/m^2}$ for clear sky conditions. Less than 40% of the global distance travelled by aircraft is due to flights during local night time. Yet, due to the cancellation of shortwave and longwave effects during daytime, night-flights contribute a disproportional 60 to 76% to the annual mean forcing. In general, regions with a significant local contrail radiative forcing are also regions for which night time flights amount to less than half of the daily total of flights. Neglecting diurnal variations in air traffic/contrail cover by assuming a diurnal mean contrail cover can therefore increase the global mean radiative forcing by up to 30%.

Scaling the 1992 forcing for the year 2000 fuel usage and accounting for differences in contrail optical depth, our forcing estimate is at the lower end but within the range of the most recent results. This reinforces the finding that some earlier published estimates of contrail radiative forcing are likely to be too large. Our study builds confidence in the calculation of contrail radiative forcing. Once the amount and optical properties of contrails are known there is relatively little uncertainty about their radiative effects. However, global model calculations of contrail radiative forcing crucially rely on scaling their contrail cover with observations. We therefore see the urgent need for an update of area mean contrail cover values derived from multi-year analyses of observational data.

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1   Introduction

Aviation can affect climate through a number of mechanisms, both directly and indirectly. The most visible one, and possibly also the mechanism than can be managed most easily, is through contrails. A contrail will form when the atmospheric conditions at the aircraft's cruise altitude – in connection with the characteristics of the aircraft exhaust – are favourable. Once formed, line-shaped contrails can persist for a few hours. Some of these persistent contrails can spread out and form cirrus clouds.

Whereas the climate effect (as measured by radiative forcing) of these contrail-induced cirrus clouds is highly uncertain, the radiative forcing due to line-shaped contrails is sufficiently known to be attributed at least a "fair" level of scientific understanding (IPCC, 1999). In its Special Report on Aviation IPCC (1999) gave a best estimate of global mean radiative forcing from line-shaped contrails in 1992 of 20 mW/m^2.

However, the IPCC estimate was based on a single study (Minnis et al., 1999), and since then the global radiative effects of contrails have been further investigated, using different datasets, models, and methods (e.g., Myhre and Stordal, 2001; Marquart et al., 2003; Fichter et al., 2005). In these studies the estimate of global mean, annual mean radiative forcing due to line-shaped contrails has been continously lowered. In 2005 the TRADEOFF project updated the IPCC's 1992 value. Based on post-IPCC studies it gave 10.0 mW/m^2 as the best estimate of contrail radiative forcing in 2000 (Sausen et al., 2005).

In global studies of contrail radiative forcing the diurnal variation of air traffic is often neglected (e.g., Marquart et al., 2003; Fichter et al., 2005). Stuber et al. (2006) investigated the effects of diurnal variations of air traffic on contrail radiative forcing over southeast England. They found that flights during the night time have a disproportionate effect on the annual, diurnal mean contrail radiative forcing.

To determine the impact of diurnal variations of air traffic on global mean contrail radiative forcing, and to see how far the results of Stuber et al. (2006) are applicable on a global scale, we performed a global calculation of the radiative forcing due to line-

shaped contrails. We derived contrail cover from a combination of diurnally resolved air traffic data, and ECMWF analysis data. This contrail cover data set has been derived independently from earlier studies and is used here for the first time. As we additionally used a sophisticated radiative transfer model our study also serves the purpose to give another independent estimate of global mean contrail radiative forcing.

2 Model description

We used the delta-4-stream version of the radiative transfer code of Fu and Liou (1992, 1993). The model includes gaseous absorption and scattering of shortwave as well as longwave radiation (Fu et al., 1997). For water clouds spherical droplets are assumed at all wavelengths. For ice clouds the optical properties in the longwave are computed using the method described in Fu et al. (1998), assuming randomly oriented hexagonal ice crystals. As well as taking part in model intercomparison exercises (Ellingson and Fouquart, 1990), the model has also been previously applied in cloud (e.g., Charlock et al., 1995; Carlin et al., 2002) and contrail studies (e.g., Meerkoetter et al.,1999; Duda et al., 2001).

Solar insolation was modified according to the Julian day of the year. To account for the diurnal cycle of solar insolation we performed calculations every 1 hour, varying the solar zenith angle accordingly. The sizes of the cloud or contrail particles were prescribed, letting the model calculate the liquid water content or ice water content needed to produce the prescribed optical depth in the visible (τ_{vis}). Generalised effective diameters (Fu, 1996) of 21 μm for high clouds and 6 μm for mid and low clouds were assumed. The generalised effective diameter of the contrail particles was calculated from the particle spectrum given in Strauss et al. (1997), which is based on both in-situ measurements and a temperature dependent parametrisation.

To test our model configuration we repeated the calculations performed by Meerkoetter et al. (1999) and Myhre and Stordal (2001; hereafter MS2001). Following Meerkoetter et al. (1999), a 100% contrail cover with τ_{vis}=0.52 was introduced into an otherwise

clear atmosphere, using a continental midlatitude summer atmospheric profile. The contrail top was located as closely as possible to 11 km.

Following MS2001 a global 1% homogeneous contrail cover ($\tau_{vis}=0.3$) was introduced at approximately 10.8 km altitude. Optical properties were prescribed according to Strauss et al. (1997). For this comparison we used seasonal mean atmospheric vertical profiles and surface data derived from a three-dimensional climatology compiled at the University of Reading, in a 20 by 10 degrees longitude/latitude resolution. This climatology is based on satellite, aircraft and ground-based observations and provides long-term monthly mean profiles of temperature and the mixing ratios of water vapour and ozone on 15 to 19 vertical pressure levels extending up to 1 hPa. Information is also given about the surface albedo and the amount, optical depth and height of low, mid, and high level clouds. Cloud information is based on ISCCP C2 data (Rossow et al., 1988).

Given the different model configurations as well as differences inherent in a comparison, e.g., differences in clouds, temperature and humidity profiles, and surface albedo, the results (Table 1) agree reasonably well for both contrail configurations. This implies that once the amount, location and properties of line-shaped contrails are known, there is relatively little uncertainty in their radiative effect. It is worth noting, however, that all global estimates of contrail radiative forcing so far are based on calculations using a plane parallel geometry. Three-dimensional radiative transfer calculations have been found to increase the longwave radiative forcing and to either increase or decrease the shortwave radiative forcing – depending on the orientation of the contrail with respect to the sun (Gounou and Hogan, 2006). Although the individual effects are relatively small, they potentially have a significant impact on the fine balance between positive longwave and negative shortwave effects. However, until 3-D effects are incorporated to re-evaluate global contrail radiative forcing calculations, best estimates of global contrail radiative forcing have to be based on plane-parallel approximations.

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3 Air traffic and contrail cover

We used gridded data from the EU FP5 project AERO2k (V1.0; see Eyers et al., 2004 for details) to calculate global contrail cover. This dataset records several aviation emissions and details of distance flown for each month in 2002 and for four six-hourly time periods – starting at midnight Greenwich Mean Time – averaged over one week in June 2002. The dataset gives a total fuel usage by civil aviation in 2002 of 156 Tg/year. From the distance-flown data for June 2002, we calculated the maximum persistent contrail cover, assuming that every flight produced a contrail of a standard width and lifetime of 2 km and 2 h, respectively. Details of this methodology can be found in Stuber et al. (2006). We scaled these result with the monthly total column air traffic for 2002 to get diurnally resolved data for each month. This latter step has the consequence that the structure of the vertical profile of maximum persistent contrail cover is fixed to the June profile over the course of the year.

Next we calculated the contrail frequency of occurrence using analysis data of the European Centre for Medium-Range Weather Forecast's integrated forecast system for the year 2004/2005. The data provides atmospheric profiles for each day of the month. We used data with a horizontal resolution of 2.5° longitude/latitude. For each layer in each gridbox we determined wether conditions were favourable for the formation of a contrail by applying a temperature/humidity criterion. Contrails formed in a gridbox if the temperature was less than 233.16 K (–40.0 °C) and the relative humidity with respect to ice exceeded 80.0%. Sensitivity studies, comparing observations of contrails over Reading with ECMWF analysis data (for 2005) showed that these choices were the optimum thresholds for maximizing the predicitive success of the analysis data (G. Rädel, personal communication).

Combining the resulting contrail frequency of occurrence with the maximum possible contrail cover we obtained the actual vertical distribution of monthly mean contrail cover for each gridbox, for each of the four six-hour time periods. Note that due to having only one week of diurnally resolved AREO2k data we had to omit possible sea-

sonal variations in the vertical distribution of air traffic (see above). Therefore, any seasonal variations in the height profile of contrails over a given location are solely due to variations in atmospheric conditions.

We calibrated the data to match satellite observations for the eastern-Atlantic/western-Europe region. In 1992, the diurnal mean, annual mean contrail cover in this Bakan Area ($30°$ W–$30°$ E, $35°$ N–$75°$ N) amounted to 0.375% (Bakan et al., 1994). This means that although flight data for 2002 was employed, by scaling the data we are effectively making a radiative forcing estimate for 1992. To enable us to perform the calculations within a reasonable time-frame we reduced the spatial resolution to 20 by 10 degrees longitude/latitude by averaging the contrail cover. Tests showed that this has a negligible effect on global and continental-scale radiative forcing numbers.

As input for the radiative transfer calculations we derived vertical profiles of the atmosphere using the three-dimensional climatology compiled at the University of Reading (see Sect. 2).

Figure 1 shows the annual variation in air traffic and global mean, monthly mean total column contrail cover, assuming random overlap of contrails in different layers. Global air traffic has a minimum in February and a maximum in August with the distance travelled by aircraft being approximately 23% larger. Nearly 94% of global air traffic are concentrated in the Northern Hemisphere, and an analysis of the AERO2k data shows that traffic is especially dense in the North Atlantic flight corridor of northern mid-latitudes. This NH concentration of air traffic has very little seasonal variation.

The annual cycle in global mean, monthly mean contrail cover is affected by both, the amount of air traffic and the meteorological conditions which determine if flights will actually form contrails. Air traffic and contrail favourable conditions peak in different seasons. Whereas the global amount of air traffic is smallest in December, January, and February, chances for the formation of contrails reach a mimimum in June, July, and August, when the relative humidity in the upper troposphere of NH mid-latitudes has its lowest values (see, e.g., Kley et al., 2000). The annual variation in contrail cover shows that it is not the annual variations in air traffic, but rather the variations in contrail

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favourable conditions which have the dominant effect on the annual cycle in contrail coverage. (Global contrail coverage is smallest in Northern Hemispheric summer with a distinct minimum in August.) Assuming random overlap, the global mean, annual mean contrail coverage, effective for 1992, is calculated to be 0.04%. Both Marquart et al. (2003) and Fichter et al. (2005) used a GCM to determine contrail favourable conditions. Using flight data for 1992 they obtained global annual mean contrail covers of 0.06 and 0.047%, respectively. Given the very different approach to calculating contrail cover, as well as differences in the flight data used, the agreement between the different estimates is encouraging.

The geographical distribution of total column contrail cover (Fig. 2) reflects the location of the major flight routings. However, the poor horizontal resolution precludes detailed features emerging. Maxima in contrail cover are seen over North America, the North Atlantic flight corridor, Europe, and the Far East.

Table 2 gives the global mean percentages of flights during the four six-hour time periods (times given are local times) as well as during local night and day time. We performed the calculations (every 1 h) in local time, determining the relevant contrail cover by converting local times into GMT. Contributions were calculated using the solar zenith angle as an indicator of night and daytime. Note that in contrast to the numbers stated in Stuber et al. (2006), "night" and "day" are no longer approximated by the time periods 18:00–06:00 and 06:00–18:00, respectively, but refer to local times of daylight and darkness. Whereas the two time periods 6:00–12:00 and 12:00–18:00 have approximately equal shares in daily total air traffic, air traffic is unequally distributed between local day and night time, and the distance travelled is split roughly 2 to 1.

The diurnal variation in air traffic strongly depends on the geographic location (Fig. 3). For Western Europe and North America, where some night flying restrictions apply to both incoming and outgoing flights, night time flights typically amount to between 20 and 40% of the total amount of flights. Flights heading for North America or Europe, where night flying restrictions are in place, have only certain time slots for departure from their home countries. Additionally, long haul flights, departing during

day time, may well fly in darkness for parts of the journey. As a consequence, over parts of the Atlantic, Pacific, and Indian ocean, as well as Asia, more than half of the daily total of air travel occurs during night time.

4 Contrail radiative forcing

As our best estimate we calculated a global, annual mean contrail radiative forcing of 2.0 mW/m^2 for 1992 all-sky conditions (Table 3, top). Night time flights contribute 60% of this forcing. During daytime, most (62%) of the contrails' longwave effects are offset by their shortwave effects. If we assume clear sky conditions the forcing is slightly (5%) larger (Table 3, bottom). The presence of natural clouds tends to reduce the magnitude of both the shortwave and longwave effects. Thus, they increase daytime net forcings, and reduce night time net forcings. In the absence of natural clouds the importance of night time flights is increased, with night time flights' contribution to the diurnal mean forcing amounting to 76%. In this case the cancellation between longwave and shortwave effects during daytime is even more pronounced than for all-sky conditions and amounts to 83%.

The geographical distribution of the annual, diurnal mean net radiative forcing (Fig. 4) shows relative maxima of contrail radiative forcing over North America, Western Europe, and the North Atlantic flight corridor. With the exception of the North Atlantic flight corridor these are locations for which night time flights account for less than 50% of daily flights (Fig. 3).

Figure 5 shows a geographical distribution of the contribution of local night time flights to the annual, diurnal mean net radiative forcing. Over large parts of the globe night time flights contribute more than half of the annual, diurnal mean net radiative forcing. For two gridboxes in the Southern Pacific the contributions are larger than 100%. A close inspection of these locations shows that air traffic and meteorological conditions are such that contrails only occur during one month, for which mean daytime forcings are negative. However, as Fig. 4 shows, the net forcing for these gridboxes is

insignificant.

In order to determine the impact of the diurnal variation of air traffic on contrail radiative forcing, we conducted an additional experiment, in which we eliminated the diurnal variation by assuming the diurnal mean vertical profile of contrail cover at all times of day. Note that, as the vertical profile of air traffic is varying during the course of the day, assuming a diurnal mean contrail cover will change not only the amount but also the vertical distribution of contrails.

In the global, annual mean, eliminating the diurnal variation of air traffic increases the amount of flights during local night time (Table 2). Accordingly, the magnitude of the shortwave forcing decreases by about 17% (Table 4). The longwave forcing slightly increases by 5%. As it is hardly affected by the solar zenith angle, the change in longwave forcing is likely to be due to changes in the vertical profiles of contrail cover. Depending on wether all-sky or clear sky conditions are assumed net radiative forcing increases by 20% (all-sky) to 30% (clear sky) when a diurnally constant contrail cover is imposed.

For those locations with a significant local forcing, i.e., the USA, Western Europe, and parts of the North Atlantic flight corridor (Fig. 4), net radiative forcings increase when the diurnal variation of air traffic is neglected. For these locations a diurnally uniform distribution of flights increases the amount of flights during local night time (Fig. 3), and thus decreases the amount of cancellation between longwave and shortwave effects.

5   Summary and conclusions

Combining AERO2k flight data with analysis data from the ECMWF's integrated forecast system, and calibrating for the 1992 contrail cover in the Bakan Area, we calculated a diurnally resolved 3-D distribution of contrail cover. In the global, annual mean, contrail cover due to line-shaped persistent contrails amounts to 0.04%. Assuming a contrail visible optical depth of 0.1, this contrail cover results in a global mean, annual mean net radiative forcing for 1992 of $2.0\,\mathrm{mW/m^2}$ for cloudy, and $2.1\,\mathrm{mW/m^2}$ for clear

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sky conditions. Note that these numbers give an estimate of the radiative forcing due to line-shaped, persistent contrails. They neither include the possible radiative effects of aged, spread contrails, nor the effects of aviation induced cirrus clouds. Currently both mechanisms are still too uncertain to have the basis for anything close to a reliable forcing estimate.

Stuber et al. (2006) found that for the south-east of England night flights contribute 60 to 80% to the annual mean forcing, despite the fact of being responsible for only 25% of the flights. Globally, the amount of night flights is larger, with almost 40% of the total distance travelled being due to flying during local night time. Their contribution to the annual mean contrail radiative forcing is very similar to that for flights over south-east England. For all-sky conditions they contribute 60% to the annual mean contrail radiative forcing. For clear sky conditions their relative importance is even higher (76%).

Table 5 compares the contrail radiative forcing obtained in this study with values from earlier studies. Myhre and Stordal (2001; MS2001) used the Sausen et al. (1998) contrail cover, which is based on the DLR inventory (Schmitt and Brunner, 1997), to calculate global contrail radiative forcing. The global mean contrail cover for this data set amounts to 0.09%, also for 1992. They scaled the data to obtain a diurnally resolved contrail cover and used a radiative transfer model to calculate contrail radiative forcing. Assuming a contrail visible optical depth of 0.3 they calculated a net forcing of $9.0\,\mathrm{mW/m^2}$. Typical contrail optical depths are now believed to be lower than 0.3. However, increasing the optical depth in our calculation to 0.3 results in a net radiative forcing of $5.0\,\mathrm{mW/m^2}$. A linear scaling of this value for a global mean contrail cover of 0.09% increases the forcing to $11.3\,\mathrm{mW/m^2}$, which is 25% larger than the equivalent value calculated by MS2001. One reason for this discrepancy is that the model used by MS2001 assumes non-scattering clouds in the longwave part of the spectrum. Scattering of longwave radiation is known to enhance the greenhouse effect of clouds and especially high clouds and contrails (e.g., Edwards and Slingo, 1996). Other reasons are most likely due to differences in the horizontal and vertical distribution of air traffic and, hence, contrails, the distribution of natural clouds, and differences in the

background meteorological conditions.

Marquart et al. (2003) also adopted the DLR inventory, but used a GCM to determine both contrail cover and optical depth. They obtained a global, annual mean contrail cover of 0.06% and a mean contrail optical depth of about 0.15. Neglecting the diurnal cycle of air traffic, but correcting their result a posteriori for the effects of longwave scattering excluded in the GCM's radiation code, they calculated a contrail radiative forcing of 3.5 mW/m^2 for 1992. They stated that including the diurnal cycle of air traffic decreased their forcing by less than 10%. Using the same GCM, but the inventory developed within the EU FP5 project TRADEOFF, Fichter et al. (2005) obtained a global annual mean contrail cover for 1992 of 0.047%. Again neglecting the diurnal variation in air traffic, they calculated a contrail radiative forcing of 3.2 mW/m^2.

Omitting the diurnal cycle of air traffic in our calculations we derived a contrail radiative forcing of 2.4 mW/m^2. Scaling this value linearly for a contrail coverage of 0.047% or 0.06% results in forcings of 2.8 mW/m^2 and 3.6 mW/m^2, respectively. Given the very different approaches to calculating contrail cover and differences in the radiation code as well as taking into account the consequences of assuming a globally and seasonally fixed contrail optical depth, our values agree very well with those of the two earlier studies. Additionally, taking into account the differences in the studies' approaches to determining contrail cover, the agreement in the amount of global, annual mean contrail cover is remarkably good.

Our study agrees with the finding of Marquart et al. (2003), that global mean contrail radiative forcing is increased, when the diurnal variation of air traffic/contrail cover is neglected. However, in contrast to Marquart et al. (2003) we found that neglecting the diurnal variation of air traffic resulted in an overestimation of the global mean contrail radiative forcing by 20% (all sky) to 30% (clear sky). Given the rather different result with respect to the relative importance of this effect we see the need for further investigations.

Our study builds confidence in calculating contrail radiative forcing. Once the amount, location and optical properties of the contrail cover are known there is rela-

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tively little uncertainty in its radiative forcing. It is therefore important to note that global estimates of contrail radiative forcing crucially rely on calibrating their contrail coverage with observations. Unfortunately, the Bakan et al. (1994) study, which gives an area-mean contrail cover for the air traffic dense region of the eastern-Atlantic/western-Europe, and which is widely used to scale modeled contrail cover (e.g., Marquart et al., 2003; Fichter et al., 2005), has so far not been updated. Therefore, although we used flight data for 2002, our estimate of contrail radiative forcing is effectively for the year 1992. Estimates of contrail RF for other years (e.g., Sausen et al., 2005) can be obtained by linear scaling with the respective fuel usage. However, this method clearly has its limitations. We therefore see an urgent need for an update of the Bakan et al. (1994) contrail cover values. Additionally it is highly desirable to have multi-year analyses of contrail cover over other regions of the globe.

A linear scaling of our 1992 forcing value (fuel usage in 1992: 112 Tg/year; IPCC, 1999) with fuel usage for the year 2000 (152 Tg/year; TRADEOFF value for fuel usage by civil aviation; Gauss et al., 2006) gives a forcing of 2.7 mW/m^2 (Table 6). The TRADEOFF best estimate of radiative forcing from linear contrails in 2000 is 10 mW/m^2, based on scaled values from MS2001 (6 mW/m^2) and Marquart et al. (2003; 15 mW/m^2). This puts our result below the lower end of radiative forcing estimates so far. This is not surprising, given that the MS2001 estimate is for a contrail optical depth of 0.3 rather than 0.1, and that the mean contrail optical depth in the Marquart et al. (2003) calculations is 0.15. Upscaling our τ_{vis}=0.3 forcing (5.0 mW/m^2) for the year 2000 fuel usage gives a forcing of 6.8 mW/m^2, which is close to the scaled MS2001 value and within the TRADEOFF range of estimates (Sausen et al., 2005).

Scaling with fuel usage in 2002 (156 Tg/year; Eyers et al., 2004) we obtain a forcing of 2.8 mW/m^2 for τ_{vis}=0.1 and 7.0 mW/m^2 for τ_{vis}=0.3. Contrail radiative forcing is small for current levels of air traffic. Sausen et al. (2005) give the radiative forcing due to the various emissions from aircraft in 2000. Their best estimates show linear contrails to have only the third largest radiative forcing (10 mW/m^2) after aviation carbon dioxide (25 mW/m^2) and aircraft-induced ozone increases (19 mW/m^2). However, air

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travel is a rapidly growing sector, and its large growth rates make contrails a potentially important factor in anthropogenic climate change. Besides that, the appropriate metric for comparing different emissions is not radiative forcing but the global warming potential GWP. Forster et al. (2006) showed that over a 100 year time horizon contrails are
⁵ roughly equivalent to aviation's carbon dioxide emissions.

Taking into account the rather different approaches to the calculation of both contrail cover and contrail radiative forcing, our estimate of annual mean, global mean contrail radiative forcing agrees reasonably well with other post-IPCC 1999 studies. This supports the conclusion by Sausen et al. (2005) that the IPCC estimate of radiative
¹⁰ forcing due to line-shaped contrails was considerably too high. Our best estimate of 2.0 mW/m^2 in 1992 suggest an overestimation of the radiative effect of linear, persistent contrails by up to a factor of 10.

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Global contrail radiative forcing

N. Stuber and P. Forster

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Table 1. Top: Radiative forcing [W/m^2] at the top of the atmosphere due to a 100% contrail cover (τ_{vis}=0.52) in a continental mid-latitude summer atmosphere. (Bottom): Annual mean, global mean radiative forcings [W/m^2] at the top of the atmosphere due to a 1% homogeneous contrail cover (τ_{vis}=0.3) for all-sky and clear sky conditions.

	longwave	shortwave	net
Meerkötter et al. (1999)	51.5	–22.0	29.5
Myhre and Stordal (2001)	45.6	–25.2	20.4
this study	44.2	–20.3	23.9

	MS2001		this study	
	all-sky	clear sky	all-sky	clear sky
longwave	0.21	0.27	0.19	0.25
shortwave	–0.09	–0.15	-0.06	-0.12
net	0.12	0.12	0.13	0.13

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Table 2. Global mean percentages of flights in the four 6-h AERO2k time periods and during night and daytime. Note that all times are local times.

0:00–6:00	06:00–12:00	12:00–18:00	18:00–24:00
14.6%	31.1%	33.1%	21.2%

night	day
36.6%	63.4%

Table 3. Global, annual mean longwave (lw), shortwave (sw), and net radiative forcing for all-sky (top) and clear sky (bottom) conditions in mW/m^2 for the four six-hour time periods (local time), as well as diurnal, night time and daytime means.

| | all-sky | | | | | | |
	0:00–6:00	6:00–12:00	12:00–18:00	18:00–24:00	mean	night	day
lw	1.89	4.18	4.46	2.84	3.34	2.35	4.30
sw	-0.05	–2.39	–2.72	-0.25	–1.35	0.00	–2.69
net	1.84	1.79	1.74	2.58	1.99	2.35	1.61

| | clear sky | | | | | | |
	0:00–6:00	6:00-12:00	12:00–18:00	18:00–24:00	mean	night	day
lw	2.55	5.68	6.05	3.86	4.54	3.22	5.85
sw	–0.10	–4.25	–4.73	–0.48	–2.39	0.00	–4.85
net	2.45	1.43	1.32	3.38	2.14	3.22	1.00

Table 4. Global, annual and diurnal mean longwave, shortwave, and net radiative forcings in mW/m^2, for both all-sky and clear sky conditions with or without diurnal variations of air traffic.

| | all-sky | |
	with diurnal cycle	w/o diurnal cycle
lw	3.34	3.52
sw	−1.35	−1.11
net	1.99	2.41

| | clear sky | |
	with diurnal cycle	w/o diurnal cycle
lw	4.54	4.78
sw	−2.39	−1.99
net	2.14	2.79

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Table 5. Comparison of contrail radiative forcing RF (in mW/m^2) calculated in this study with results from earlier studies. "Scaled" indicates values that have been linearly scaled with contrail cover (in %). For the two studies with a variable optical depth, the mean value of τ is given.

study	contrail cover	τ	diurnal cycle air traffic	RF
this study	0.04	fixed, 0.1	yes	2.0
this study	0.04	fixed, 0.3	yes	5.0
MS2001	0.09	fixed, 0.3	yes	9.0
this study, scaled	0.09	fixed, 0.3	yes	11.3
this study	0.04	fixed, 0.1	no	2.4
Marquart et al. (2003)	0.06	variable, 0.15	no	3.5
this study, scaled	0.06	fixed, 0.1	no	3.6
Fichter et al. (2005)	0.047	variable, 0.15	no	3.2
this study, scaled	0.047	fixed, 0.1	no	2.8

Table 6. Contrail radiative forcing in mW/m^2 for different time horizons, obtained by a linear scaling with fuel usage. Fuel usage in 1992, 2000, and 2002 was 112, 152, and 156 Tg/year, respectively. The TRADEOFF best estimate of 10 mW/m^2 for 2000 is based on scaled values from studies by MS2001 and Marquart et al. (2003), which are cited in this table.

study	year	τ	RF
this study	1992	fixed, 0.1	2.0
MS2001 (scaled)	2000	fixed, 0.3	6
Marquart et al. (2003) (scaled)	2000	variable, 0.15	15
this study, scaled	2000	fixed, 0.1	2.7
this study, scaled	2000	fixed, 0.3	6.8
this study, scaled	2002	fixed, 0.1	2.8
this study, scaled	2002	fixed, 0.3	7.0

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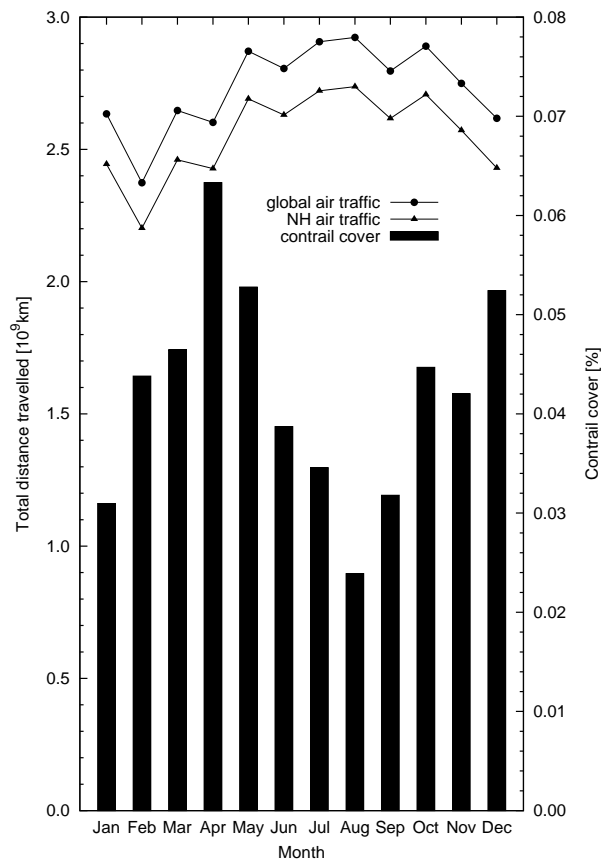
Fig. 1. Annual cycle of global and Northern Hemispheric air traffic (distance travelled in 10^9 km), and global mean, monthly mean contrail coverage (in %).

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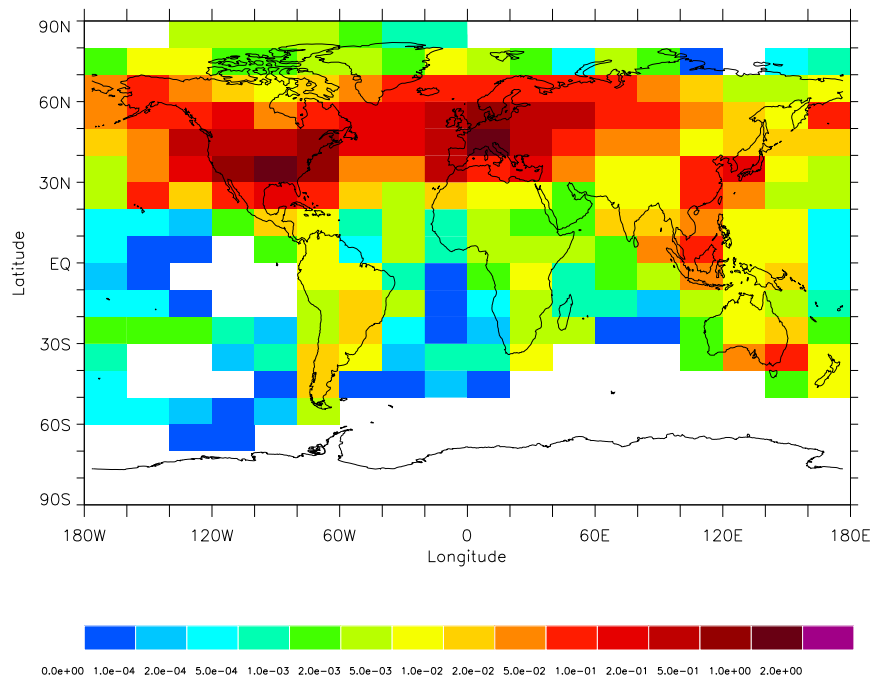
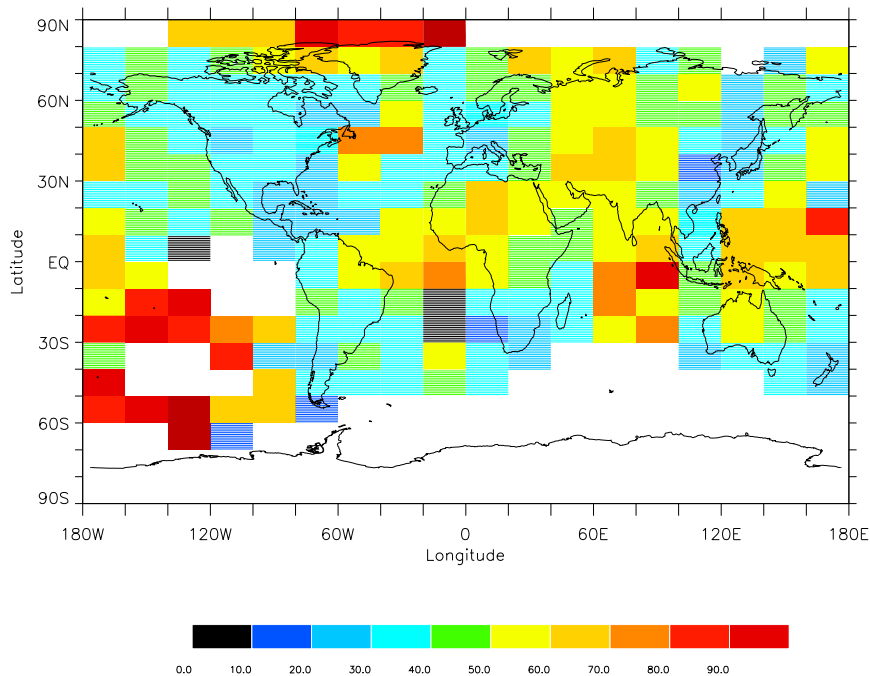**Fig. 2.** Annual mean, diurnal mean contrail cover, in percent. Note the logarithmic scale.

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Fig. 3. Percentage of flights during local night time. Values higher than 50% are indicated by solidly filled boxes.

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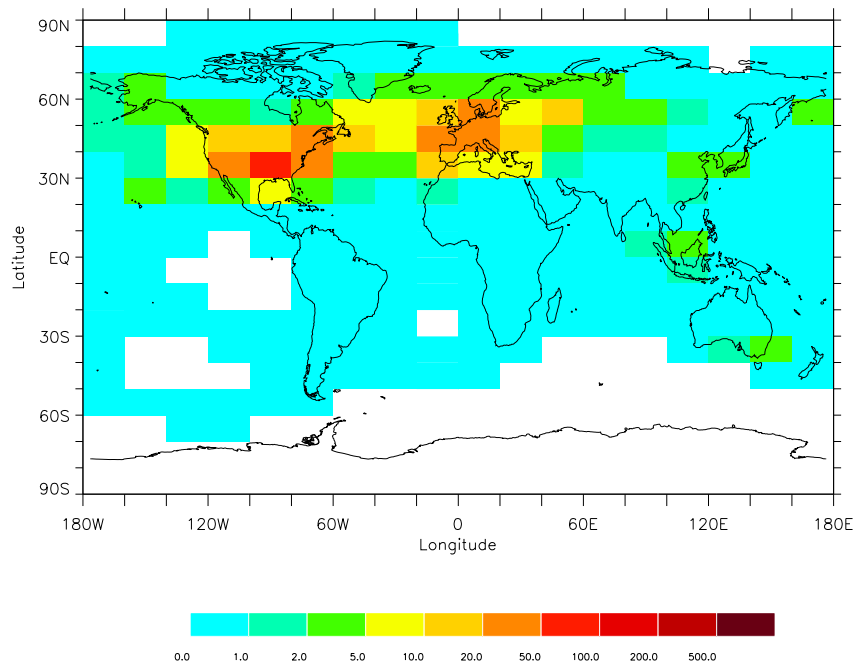
Fig. 4. Annual, diurnal mean net radiative forcing in mW/m^2, for all-sky conditions. Note the logarithmic scale.
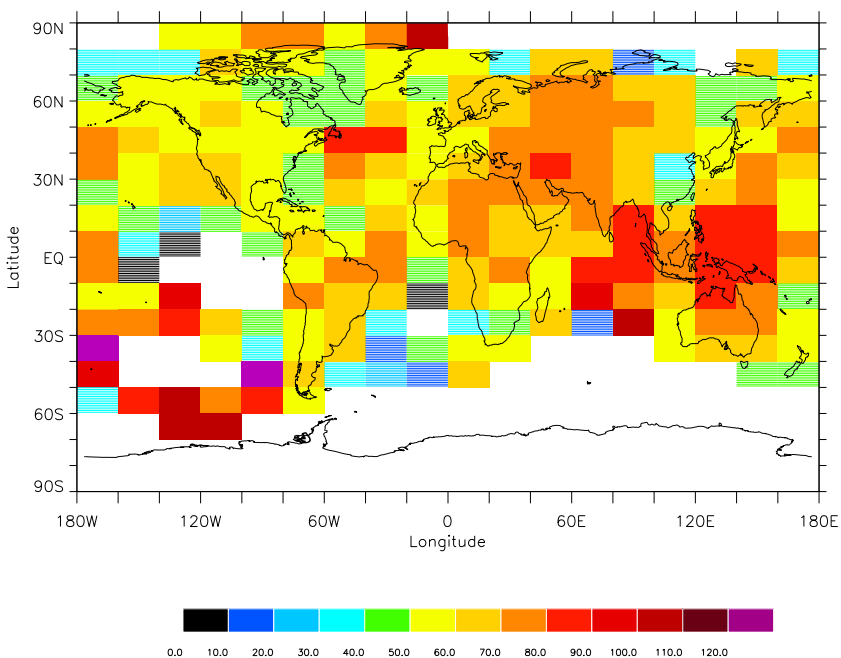
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Fig. 5. Percentage contribution of flights during local night time to the annual mean diurnal mean contrail radiative forcing. Contributions less than 50% are indicated by striped boxes, contributions higher than 50% by solidly filled boxes.