Atmos. Chem. Phys. Discuss., 11, 19927–19952, 2011
www.atmos-chem-phys-discuss.net/11/19927/2011/
doi:10.5194/acpd-11-19927-2011

Atmospheric Chemistry and Physics Discussions

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Sensitivity of radiative properties of persistent contrails to the ice water path

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Received: 13 April 2011 – Accepted: 22 June 2011 – Published: 13 July 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The dependence of the radiative properties of persistent linear contrails on the variability of their ice water path is assessed in a two-stream radiative transfer model. It is assumed that the ice water content and the effective size of ice crystals in aged contrails do not differ from those observed in natural cirrus; the parameterization of these two variables, based on in situ observations, allows a more realistic representation than the common assumption of fixed values for the contrail optical depth and ice crystal effective radius.

The results show that the large variability in ice water content that aged contrails may share with natural cirrus, together with an assumed contrail vertical thickness between 220 and 1000 m, translate into a wider range of radiative forcings from linear contrails (0.3 to 51.6 mW m^{-2}) than that reported in previous studies, including IPCC's (3 to 30 mW m^{-2}). The derivation of a best estimate within this range is complicated by the fact that the ice water contents measured in situ imply mean optical depths between 0.08 and 0.32, coinciding with the range commonly assumed in contrail studies, while optical depths derived from satellite ice water content retrievals are significantly larger (0.51–2.02). Further field and modelling studies of the temporal evolution of contrail properties will thus be needed to reduce the uncertainties associated with the values assumed in large scale contrail studies.

1 Introduction

Contrail radiative studies generally assume a fixed particle size distribution (PSD) in the ice cloud (e.g., Strauss et al., 1997; Meerkötter et al., 1999; Minnis et al., 1999) and a fixed optical depth (OD) (e.g., Minnis et al., 2004; Stuber and Forster, 2007; Rädel and Shine, 2008). This simplification is made in response to the large uncertainties in the characterization of ice cloud PSDs (e.g., McFarquhar et al., 2007; Jensen et al., 2009) and the large variability found in ice cloud micro- and macro-physical properties, which

ACPD
11, 19927–19952, 2011

must be taken into account when deriving representative values for large scale contrail simulations.

In most radiative transfer applications ice clouds are represented by two parameters, namely their ice water content (IWC) and a metric of their size spectrum, such as the effective radius or Fu's generalized size parameter (Fu, 1996). Contrail crystals may differ, both in shape and concentration, from those observed in natural cirrus under the same conditions (Poellot et al., 1999); how much the physical properties of these crystals are determined by their anthropogenic origin and how much by the atmospheric environment is not clear (e.g. Jensen and Toon, 1997; Schumann et al., 2010). Recent measurements, such as those from the mid-latitude field campaign CIRRUS III (Schäuble et al., 2009) have shown that the ice water contents in cirrus and aged contrails are similar under the same atmospheric conditions, while ground-based observations of an aged contrail made by Atlas and Wang (2010) have confirmed that the IWC of linear contrails can reach values close to the upper limit for mid-latitude cirrus.

More extensive contrail field measurements are needed but, given the small differences between the IWC in natural cirrus and in aged contrails at the same temperature and the fact that the radiative forcing (RF) of ice clouds is mainly determined by their ice water path, it seems reasonable to use a characterization based on cirrus measurements to represent the developed stages of contrails, as has been done previously (e.g., Wyser and Ström, 1998; Ponater et al., 2002).

In order to investigate the sensitivity of the global RF of persistent linear contrails to such an assumption, we set up a model with a fixed homogeneous mono-layer contrail cover with a representative range of physical depths and altitudes, and assess the effect of this layer on the local and global radiation fields, allowing its ice water content and effective ice crystal size to vary as a function of ambient temperature.

ACPD
11, 19927–19952, 2011

2 Model simulations

The physical properties of both, aged contrails and natural cirrus are prescribed in the model simulations using Schiller et al.'s (2008) IWC climatology and the PSD parameterization of McFarquhar and Heymsfield (1997), based on ice cloud observations in the tropics covering a temperature range from −30° to −60 °C.

The range of observed cirrus IWCs compiled by Schiller et al. is represented in Fig. 1 (top), with fitted curves being shown for minimum, mean, and maximum measured values (dotted, solid and dashed lines, respectively) as functions of temperature. These fits are used as input in McFarquhar and Heymsfield's PSD parameterization at six temperature values, covering a range from 195 to 245 K, to produce 18 PSDs. The generalized size (D_{ge}) (Fu, 1996) calculated for these distributions ranges from 11 to 75 µm. The 6 PSDs corresponding to the mean IWC fit, are plotted in Fig. 1 (middle) as functions of the particles' equivalent-volume diameter.

The single scattering properties (extinction coefficient, single scattering albedo, and asymmetry parameter) of ice crystals modelled as randomly oriented hexagonal prisms are integrated over the 18 PSDs and parameterized in terms of their IWC and D_{ge}: such a hexagonal prism habit matches both the total volume and projected areas retrieved by McFarquhar and Heymsfield, making the micro-physical and the optical properties in the model consistent. The databases of the optical properties for other habits currently available to us did not fulfill this consistency requirement. We therefore only use hexagonal prisms in our modelling. The methodology presented in Fu et al. (1998) is used to integrate the long-wave (LW) optical properties calculated by Baran et al. (2001). In the shortwave (SW), the parameterization described by Fu (1996) and the single scattering properties calculated by Yang et al. (2000) are applied. The SW and LW parameterizations are incorporated into the Edwards and Slingo two-stream radiative transfer model (Edwards and Slingo, 1996) with a configuration of 6 and 9 bands in the SW and in the LW spectral regions, respectively.

ACPD
11, 19927–19952, 2011

The uncertainties in the characterization of the relative abundance of small crystals may affect the calculated radiative properties of ice clouds (McFarquhar et al., 2007). In order to ensure an accurate representation of the relative concentration of small particles in the model, the total ice number concentrations used here are compared with those compiled by Krämer et al. (2009), which provide quality-checked aircraft in situ observations of ice crystal numbers performed during 28 flights in tropical, mid-latitude and Arctic field experiments, covering latitudes from 20° South to 75° North. The comparison (Fig. 1, bottom) suggests that despite the fact that McFarquhar and Heymsfield's PSDs are limited to one campaign, the dependence of the relative small crystal concentration on temperature is consistent with values retrieved at a wide range of latitudes.

The background meteorology used in the model is based on monthly climatological data for water vapour, ozone, temperature, and surface albedo from ECMWF (Simmons and Gibson, 2000). Three-dimensional distributions of low, middle and high cloud cover, and cloud total water path from the International Satellite Cloud Climatology Project (ISCCP) D2 (Rossow and Schiffer, 1999) are used; these are converted into total water contents based on the layer's physical depth. These cloud fields are monthly averages of ISCCP's three-hour resolution data, interpolated to a 2.5°×2.5° regular latitude/longitude grid and 23 layers in the vertical, extending up to 1 hPa. The total water paths of all clouds from ISCCP are separated into their liquid and solid components using Schiller et al.'s climatology, and scaled linearly in order to obtain a cloud SW RF in reasonable agreement with satellite estimates. An increase of 80 % of the total water contents from ISCCP results in a global annually averaged SW cloud RF of 47.7 $\mathrm{W\,m^{-2}}$, which compares well with the estimate of 48 $\mathrm{W\,m^{-2}}$ from the Earth Radiation Budget Experiment (ERBE) mission (Li and Leighton , 1993). This calibration of the estimated natural cloud RF in the model, and the fact that the clouds' phase partition is consistent with the prescribed contrail's IWC, will ensure a more realistic representation of the the relative contribution of contrails to the radiative impact of natural clouds and their interdependencies.

ACPD
11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

The total water contents from ISCCP are assumed to be ice-only at temperatures below −39° and liquid-only above −10°C; between these two temperatures, the total water content from ISCCP is partitioned according to Schiller et al.'s IWC climatology, using a fitted curve to the maximum observed IWC values in which only observations with frequencies larger than 5 % are included. This is shown by the red dashed curve in Fig. 1. A fit to the maximum, rather than to the mean, IWC is used because it roughly approximates the range of IWCs retrieved from the ISCCP data for ice clouds: these show considerably larger values than the values for mean IWC reported by Schiller et al. The D_{ge} of the solid phase is prescribed as a function of the IWC and temperature of the cell according to McFarquhar and Heymsfield's parameterization. For the liquid cloud phase, spherical droplets with an effective radius of 10 µm are assumed.

The contrail cover layer is taken from Fichter et al. (2005) who, based on the TRADE-OFF inventory of aircraft flown distance for the year 1992, found an annual mean global cover of 0.047 %. Their vertically integrated 2-D contrail cover (CC) distribution is based on a random overlap assumption, it being assumed in the radiative transfer calculations that clouds in adjacent layers are maximally overlapped, while groups of clouds separated by one or more clear layers are randomly overlapped ("maximum-random overlap").

The shortwave (SW), long-wave (LW) and net (SW+LW) instantaneous RFs are calculated at the top of the atmosphere for two representative months, January and July. The solar zenith angles and day lengths at the middle of the month are used to represent the month's SW average. The diurnal cycle is approximated by a Gaussian integration of 5 solar zenith angles. No diurnal dependence is assumed on the CC extent, as no global estimate of contrail lifetimes is available at present.

In the simulations, unless stated otherwise, mean observed IWC values from Schiller et al. are prescribed at the centre of a 1000 m thick contrail layer positioned at 200 hPa (~38 000 ft) with a realistic horizontal cover for year 1992. Given that the vertical resolution in the model is variable (between 1 and 2 km), it is necessary to adjust the contrail's horizontal extent when contrail and cirrus coincide in the same cell. In this

ACPD
11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

case, the contrail's contribution to the cloud cover is re-scaled to preserve its mass.

3 Results

The geographical distributions of the calculated contrail net RFs are shown in Figs. 2 and 3, with a global average of 7.6 $mW\,m^{-2}$ in January and 2.6 $mW\,m^{-2}$ in July. The maximum monthly mean of 360 $mW\,m^{-2}$ occurs over Northwest USA in January. The fact that the global mean CC in January is 0.078 % compared to only 0.038 % in July, partly explains the larger effect of contrails in January. Other factors, however, including the background meteorology, the albedo and the natural cloud cover, also contribute to this seasonal variability, and enhance the weighted net contrail RF in January (see Fig. 6).

The impact that natural clouds have on the calculated contrail RF is assessed by comparing modelled results for clouds being present or absent. The Northern Hemisphere's (NH) zonal RF profiles for the "all sky" and "clear sky" (contrails only) cases and their global means are presented in Fig. 4, showing that the presence of natural clouds reduces RF slightly more in the SW than in the LW, thereby somewhat reducing the net RF. Locally this is not always the case, as it can be seen in the July profiles at latitudes higher than 60° N: here the contrails' net RF is actually enhanced by natural clouds. This effect tends to occur over high latitude ice free regions, where contrails can show negative net RFs in the absence of other clouds. As can be seen in Fig. 4, however, the zonal mean always remains positive.

Natural clouds in the model are responsible for a reduction of around 40 % in the annual contrail net RF, which contrasts with less than 10 % reported in previous studies (e.g., Myhre et al., 2001; Stuber and Forster, 2007; Rädel and Shine, 2008). It is possible to obtain contrail net RF reductions as small as 11 % from natural clouds in our model if random overlap is assumed, but we regard the maximum-random overlap model to be more realistic in this context.

ACPD
11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

In order to assess the sensitivity of a contrail's RF to its altitude, while excluding any dependence on its horizontal extent, four pressure levels (300, 250, 200 and 150 hPa), representative of the cruise altitudes with significant CC, are used. These pressure levels roughly correspond to flight levels FL300, FL340, FL380, and FL400 (i.e. altitudes of 30 000, 34 000, 38 000, and 40 000 ft). The same CC is prescribed at these levels and their RFs are compared.

At middle latitudes in the NH, where most traffic is concentrated, around 70 % of the distance travelled by aircraft occurs between FL340 and FL380. This, together with the dependence of contrail formation on meteorological conditions, means that FL300 and FL400 have a comparatively much smaller CC. The potential CC, defined as the fraction of the sky that would be covered by contrails if traffic were present everywhere and all the time, can be negligible at these flight levels in some cases, for example for low latitude flights at FL300 in January and FL300 and FL340 in July. This is also the case for high latitude flights at FL400 in July. Despite the small likelihood of contrails being formed in these cases, the results of their radiative properties are still included for comparison purposes. At middle latitudes, contrail formation is possible at all four flight levels.

Figure 5 shows the mean net RFs for the NH, which present slightly larger values for FL300 in January (8.8 $\mathrm{mW\,m^{-2}}$, global average) and FL400 in July (3.5 $\mathrm{mW\,m^{-2}}$). Other cruise altitudes show more modest impacts in both months with values of around 7.7 $\mathrm{mW\,m^{-2}}$ in January and around 2.6 $\mathrm{mW\,m^{-2}}$ in July. These differences are related not only to the dependence of the contrail radiative properties on the ambient temperature, and therefore on its altitude, but also to the background conditions, i.e. meteorology, natural cloud cover and local albedo. Despite the fact that FL340 and FL380 show similar global mean RFs for the two months, their zonal profiles show significant differences.

The RF's dependence on altitude can be seen more clearly if the RF is weighted by the CC, as in Fig. 6, which shows the net RF per percentage CC. These profiles follow a similar zonal pattern to that of the predicted IWC (not shown), with the largest

ACPD
11, 19927–19952, 2011

altitude sensitivity predicted to occur at low latitudes, where the radiative impact of contrails decreases markedly with altitude. This behaviour changes at middle latitudes (at around 40° N) in both months. The modest altitude dependence predicted for January between FL340, FL380, and FL400, at middle latitudes –where most traffic is concentrated – implies that the effect of contrails in winter should mainly be driven by the potential CC, which decreases with altitude. In July, on the other hand, the weighted RF shows a significant altitude dependence, with FL340 showing weighted RF values smaller than those at FL400 by as much as a factor of 10 at some heavily trafficked latitudes.

Strategies for contrail impact reductions may therefore depend on the season but, given that the the potential CC (not included here) has a strong seasonal dependence, it is important to consider the radiative and the contrail formation aspects using mutually consistent models. The dependence of contrail formation and chemistry on altitude, which should also be considered in mitigation strategies, are beyond the scope of the present study.

The OD of ice clouds is determined by their particle habit and their ice water path, defined as the IWC integrated over the vertical extent of the cloud. No climatology of contrail vertical thickness is available at present, but a range of values can be tested in order to assess the sensitivity of contrail RF to its OD. A case of a contrail with a maximum OD of 2.3 and a corresponding vertical thickness of 1 km, was reported by Atlas and Wang (2010) based on Lidar retrievals; this value is used here as the upper bound for the possible range of contrails' vertical thickness while a lower bound of 220 m is chosen. The latter was used by Minnis et al. (1999) to approximate the RF of contrails by a single layer positioned at 200 hPa. We have confirmed the validity of this approximation in our model by comparing the results of a 3D distribution with those of the vertically integrated CC. This showed differences in the RF monthly averages of less than 10 %.

In order to assess the RF sensitivity to a contrail's IWC, three cases are compared. These cases are defined by the fitted curves to the mean, minimum and maximum

ACPD
11, 19927–19952, 2011

IWC in Schiller et al.'s compilation (see Fig. 1). In the cases of the minimum and the maximum IWCs, frequencies smaller than 5 % were excluded from the fits (red curves in the top panel of Fig. 1); for natural cirrus, this maximum IWC fit is always assumed. The results, presented in Fig. 7, show a greater sensitivity in January than in July. This is a consequence of the greater sensitivity of the IWC to temperature observed in Fig. 1 at lower temperatures.

The dependence of the global mean RFs on the IWC is summarized in Table 1. This shows the monthly mean OD, the ice water path and the generalized size parameter, as well as their annual means. Here it should be noted that the average of January and July serves as a proxy for the annual mean. Both the OD and the net RF show a sensitivity to the IWC variability of around two orders of magnitude. The sensitivity to the contrails' vertical thickness, on the other hand, is only around a factor of 2, as it can be seen from the differences in the RF for 220 m and 1000 m physical depths with the same IWC.

The predicted range of D_{ge} spans a factor of 3, with a 25 µm D_{ge} being predicted over the NH if mean values for IWC are assumed; this value is similar to that (23.5 µm) for the contrail PSD commonly assumed in off-line contrail studies (Strauss et al., 1997), showing that this PSD does not differ significantly from that of typical cirrus at contrail altitudes. Despite the significant variability in the predicted D_{ge} observed in Table 1, the sensitivity of the RF to D_{ge} cannot be assessed independently of the IWC variability without inconsistent micro-physical assumptions.

4 Discussion

Off-line radiative transfer studies for contrails usually assume fixed OD values, between 0.1 and 0.5, with a recent trend towards the lower end of this range. Representative OD values are normally derived from satellite data because of their large scale coverage, but the detection of persistent contrails by passive remote sensing instruments requires them to reach the detection thresholds for OD and horizontal extent while retaining

ACPD
11, 19927–19952, 2011

their linear shape; this limitation may introduce biases into the physical and temporal properties derived statistically from satellite retrievals.

In the present study if the IWC variability is neglected, and only the vertical thickness is allowed to vary, the predicted range of mean annual global OD values (0.08, 0.32) for contrails between 220 and 1000 m, matches the range of values commonly assumed in recent off-line studies. The results presented by Ponater et al. (2002), based on on-line contrail simulations, also fall within this range, as they reported an annual global mean OD of 0.15 for a 700 m thick contrail. Using the same vertical depth as was prescribed by the resolution of Ponater et al.'s model, the setup used here produces an OD of 0.23.

Ponater et al. reported a variability in global contrail OD that shows similarities with our findings. They predict maximum monthly values to be larger than the mean by an order of magnitude; this is confirmed in our study, but important differences with Ponater et al.'s results, however, occur on a regional level. Their predicted ODs over the USA show a large seasonal variability (0.04 to 0.25), whereas we find only a modest variability (0.29–0.34) (<20 %, assuming a 1000 m vertical thickness), in closer agreement with satellite retrievals by Palikonda et al. (2005), who reported a summer maximum 20–30 % greater than the February minimum.

Over the annual average, we find the mean OD over the USA to be similar to the NH average, while Europe shows values about 10 % smaller. Ponater et al. similarly found thicker contrails over America but with a larger seasonal variability than in Europe. This contrasts with the values presented here, in which contrails in Europe show a considerably boader variability, with the mean OD reaching values at least 50 % larger in July than in January, resulting in contrails being optically thinner than over the USA during the winter but optically denser during the summer. Ponater et al.'s value of 0.06 falls outside the range predicted here for Europe (0.07–0.28), but the satellite-retrieved value of 0.11 reported by Meyer et al. (2002) falls within it. The fact that the satellite estimate over Europe falls close to our lower bound, while Palikonda et al.'s satellite OD estimate over the USA (0.27) falls closer to the upper bound of our range (0.08, 0.32) for

ACPD
11, 19927–19952, 2011

that region, can be explained by the larger seasonal variability predicted over Europe. This variability translates into ODs being smaller than 0.2 during the winter, implying a reduced detectability by passive remote sensing instruments according to Kärcher et al. (2009) who, based on an analytical micro-physical cloud model, concluded that passive satellite remote strongly underestimate the ocurrence frequency of contrails with optical depths <0.1–0.2.

Kärcher et al. reported mean contrail-cirrus visible ODs of between 0.05 and 0.5 over the USA; this range is slightly broader than the NH range found here [0.08-0.32] for mean IWCs, but significantly smaller than when the full IWC variability is taken into account (0.005–2.02). It is important to remember that the range of cirrus IWCs derived from satellite retrievals falls closer to the maximum IWC fit reported by Schiller et al. than to the mean. As a consequence we produced a new maximum IWC fit to better emulate satellite retrievals. If this fit is assumed for contrails, the predicted contrail ODs increase substantially and produce a range of values (0.51–2.02) which should be regarded as more consistent with satellite measurements of IWCs. As already mentioned, the detection of linear contrails by passive remote sensing techniques is affected by many factors, but given that in the present study we assume that the contrail IWC dependence on temperature does not differ greatly from that of cirrus, it seems sensible to regard this higher range as more consistent with our model setup. Both, theoretical simulations and field measurements of contrails include maximum ODs within this higher range; Ponater et al. reported monthly maximum ODs over the USA as large as 3, while Atlas and Wang's lidar retrievals detected a 1 km thick persistent linear contrail with an OD around 2.3.

Minnis et al. (1999) performed off-line contrail RF calculations assuming fixed ODs between 0.1 and 0.5 and also included a case with a variable contrail IWC. The latter produced a RF of 10 $\mathrm{mW\,m^{-2}}$; this value falls very close to their result (8 $\mathrm{mW\,m^{-2}}$) for a fixed OD of 0.1. This OD is similar to the one obtained here (0.08) for the same physical depth assuming mean IWC values, although the corresponding RF calculated by Minnis et al. is larger than our value (2 $\mathrm{mW\,m^{-2}}$) by around a factor of two, bearing

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

in mind that their CC is almost twice as large as the one used here. This difference in the calculated RF is similar to that expected from model discrepancies; in a recent intercomparison of contrail global RF models (Myhre et al., 2001) found differences of around a factor of 2 for an assumed 1 % homogeneous global CC, and slightly smaller differences for a realistic cover.

Minnis et al. also considered the high end of the OD values retrieved by satellite to be more consistent with satellite calibrated estimates of the CC, and reported their best estimate to be 20 mW m^{-2}, based on the assumption of a fixed OD of 0.5. These results are consistent with our calculations for the same physical depth (220 m) and our maximum IWC assumption, which produces a mean NH OD of 0.51 and a RF of 11.2 mW m^{-2} for the same year (1992), that can be scaled up linearly to 21.5 when considering that the CC used in Minnis et al. is 0.09 instead of the 0.047 % used here.

Based on the fitted curve for the maximum IWC, a range of RFs bewtween 16.2 and 51.6 mW m^{-2} is obtained for year 2005 (see Table 1) by linearly scaling up the 1992 RF using the traffic increase and excluding any climate change effects. IPCC's best estimate of 10.0 mW m^{-2} falls outside this range, as do more recent estimates, which tend to be smaller than that of the IPCC (2007). In this estimate a scaling factor of 1.45 is used to take into account the increase in traffic from 1992 to 2005 (Lee et al., 2009), and a factor of 2 is applied to the upper bound of the range in order to allow for the uncertainty in the estimated CC. Also using these scaling factors, the mean IWC assumption produces a RF range (2.9–14.8 mW m^{-2}) that is similar to the values found in the recent literature, but is inconsistent with the IWC retrieved for cirrus from satellite measurements: these show much larger values than those retrieved in situ for the same temperatures. Finally, a range of RFs between 0.3 and 51.6 mW m^{-2} is obtained for year 2005 if the variabilities in vertical depth and in IWC are assumed in conjunction with the above scaling factors.

ACPD
11, 19927–19952, 2011

5 Conclusions

The variability in IWC that persistent aged contrails may share with natural cirrus implies larger uncertainties in RF than has been predicted by satellite and theoretical studies. Based on the range of vertical thickness assumed here (220 to 1000 m) a sensitivity of around a factor of 2 is found for the calculated contrail RF and OD, compared to an IWC dependence that exceeds one order of magnitude; translating into a wider range of radiative forcings from linear contrails than that reported in previous studies, including IPCC's (3 to 30 mW m^{-2}). A range of RFs between 0.3 and 51.6 mW m^{-2} is obtained here for year 2005 if both the vertical depth and the IWC variabilities are taken into account and an uncertainty of a factor of two is assumed for the CC. Minimum, mean, and maximum IWCs measured in situ imply mean optical depths in the range (0.005–0.04), (0.08–0.32) and (0.51–2.02), respectively, with corresponding RFs (0.3–1.2 mW m^{-2}), (2.9–14.8 mW m^{-2}), and (16.2–51.6 mW m^{-2}). Contrail cover estimates rely on satellite retrievals, which tend to overestimate the IWCs when compared to in situ measurements but do coincide with the contrail OD derived from in situ mean IWCs. This inconsistency demonstrates the need for collocation studies, in which ground based remote sensing retrievals, despite their limited spatial coverage, would improve our understanding of the temporal evolution of contrails and would also allow representative satellite values to be derived.

It is found that, for a fixed CC, the contrail's RF dependence on altitude is mainly linked to the IWC predicted at the different flight levels, showing a modest altitude dependence in January at heavily trafficked latitudes. This implies that the effect of contrails in winter would be largely driven by the potential CC, which decreases with altitude, In contrast, the July weighted RF shows a significant altitude dependence, with FL340 showing smaller values than FL400 in by as much as a factor of 10 at some heavily trafficked latitudes.

The predicted range of D_{ge} spans a factor of 3, with a 25 µm D_{ge} being predicted over the NH if mean values for IWC are assumed. The fact that this value is similar to that

(23.5 µm) for the contrail PSD commonly assumed in off-line contrail studies, shows that this PSD does not differ significantly from that of typical cirrus at contrail altitudes. Despite the significant variability in the predicted D_{ge}, and the fact that matching a variable IWC to a fixed D_{ge} value involves obvious physical inconsistencies, the best estimate of 20 mW m^{-2} reported by Minnis et al. (1999), based on a fixed OD of 0.5 and a fixed averaged particle size, is comparable to the results found here (21.5 mW m^{-2}) if their CC of 0.09 and vertical thickness of 220 m are assumed. The OD predicted here (0.51) for a 220 m thick contrail layer when using the maximum IWC assumption also coincides with the value used in Minnis et al.'s best estimate, who considered the high end of the OD values retrieved by satellite to be more consistent with satellite-calibrated estimates of the CC, but RFs almost twice as large are obtained if a contrail vertical thickness of 1000 m is assumed.

Acknowledgements. This work was supported by the United Kingdom Department for Transport. The authors wish to thank a number of people for providing us with the data used in this study. Christine Fichter for providing the contrail cover distribution data calculated during the TRADEOFF project. (TRADEOFF was a project in the European Fifth Framework Programme, http://www.iac.ethz.ch/tradeoff/); Piers Forster for the climatology of the monthly atmospheric composition, cloud cover and surface albedo, and Anthony Baran for the hexagonal prisms database. We thank our colleague, Michael Bennett for valuable discussions and his help to improve the readability of the manuscript. We also thank two anonymous referees and the editor for their helpful comments and suggestions.

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ACPD

11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

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ACPD
11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

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ACPD
11, 19927–19952, 2011

ACPD

11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

Table 1. Global mean top-of-the-atmosphere shortwave (SW), long-wave (LW), and net contrail radiative forcing ($\mathrm{mW\,m^{-2}}$) for the three IWC assumptions (minimum, mean and maximum). The annual mean global contrail cover (CC) is 0.047 %, as calculated in the TRADEOFF inventory of aircraft flown distance for the year 1992 and scaled up CC values for year 2005 and a further factor of 2 scale up to allow for CC uncertainties. The mean optical depth (OD), generalized size (D_{ge} in μm), and ice water path (IWP in $\mathrm{g\,m^{-2}}$) correspond to the NH averages.

IWC	Month	OD	D_{ge}	IWP	SW	LW	Net 1992	Net 2005	Net 2005 (CC X 2)
Min 220 m	Jan	0.005	12.1	0.05	−0.01	0.28	0.27		
	Jul	0.006	12.2	0.07	−0.03	0.18	0.15		
	Annual	0.005	12.1	0.06	−0.02	0.23	0.21	0.3	
Min 1000 m	Jan	0.03	13.6	0.2	−0.3	0.8	0.5		
	Jul	0.04	14.1	0.3	−0.3	0.5	0.2		
	Annual	0.04	13.9	0.2	−0.3	0.7	0.4		1.2
Mean 220 m	Jan	0.07	23.3	1.6	−1.5	4.5	3.0		
	Jul	0.09	24.0	2.0	−1.7	2.7	1.0		
	Annual	0.08	23.2	1.7	−1.6	3.6	2.0	2.9	
Mean 1000 m	Jan	0.28	26.2	3.2	−3.6	11.2	7.6		
	Jul	0.36	26.4	4.2	−4.8	7.4	2.6		
	Annual	0.32	26.3	3.7	−4.2	9.3	5.1		14.8
Max 220 m	Jan	0.47	29.2	13.1	−6.5	24.0	17.7		
	Jul	0.55	28.6	15.5	−9.1	13.7	4.7		
	Annual	0.51	28.6	13.8	−7.8	18.9	11.2	16.2	
Max 1000 m	Jan	1.88	35.7	27.0	−9.8	38.8	29.0		
	Jul	2.17	37.0	32.2	−17.3	23.8	6.5		
	Annual	2.02	36.3	29.6	−13.6	31.3	17.8		51.6

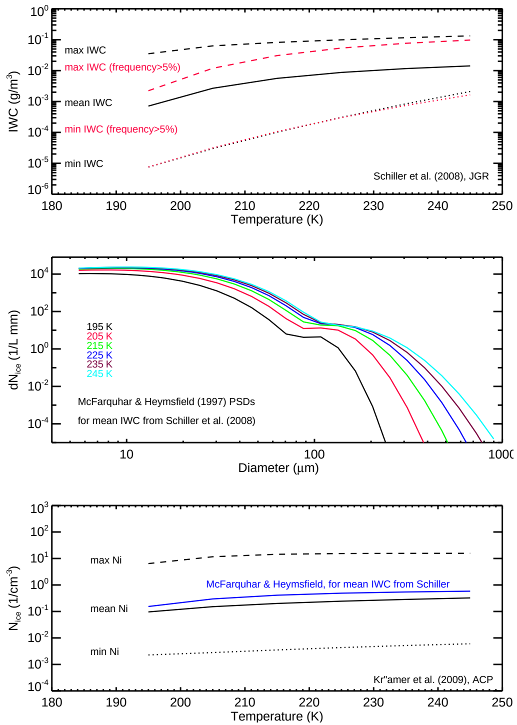

Fig. 1. Minimum, mean, and maximum IWC fits from Schiller et al., the red lines correspond to the the same dataset but including IWCs with frequencies larger than 5 % only. Middle: Particle number densities as a function of equivalent-volume diameter, based on McFarquhar and Heymsfield's parameterization and Schiller et al.'s mean IWC. Bottom: Minimum, mean, and maximum total ice crystal numbers observed by Krämer et al. (2009) compared to the total ice crystal number for mean IWC in the present study, shown in blue.

ACPD
11, 19927–19952, 2011

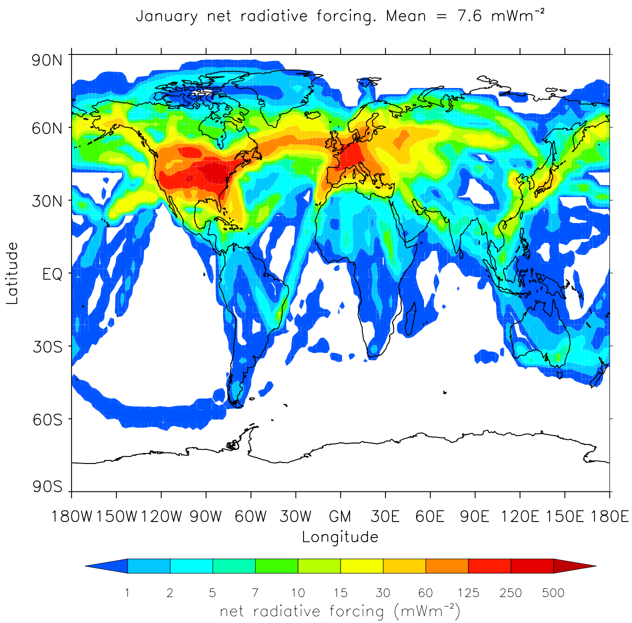

Fig. 2. Net January contrail radiative forcing for mean IWC.

ACPD
11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

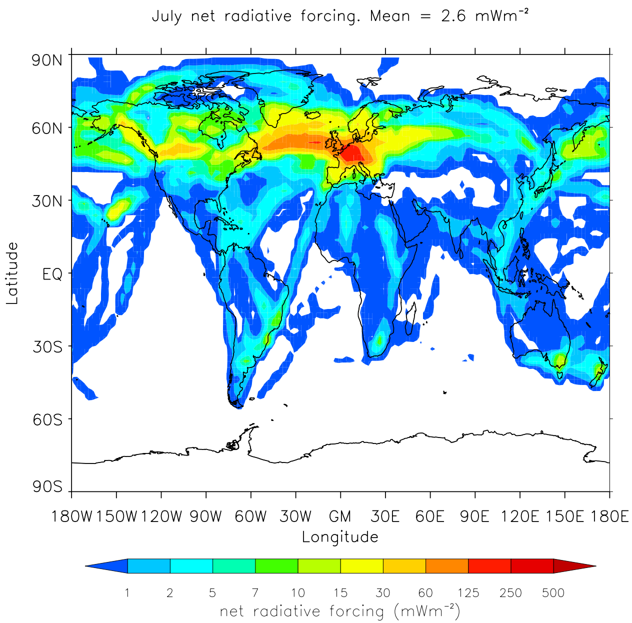

Fig. 3. Same as Fig. 2 but for July.

ACPD
11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

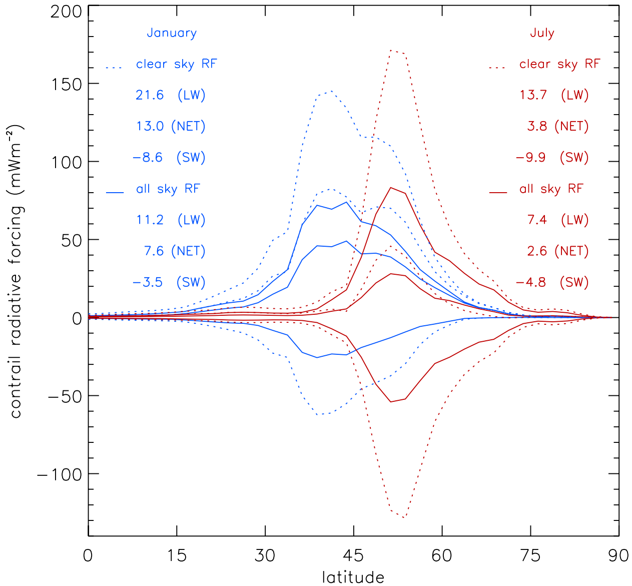

Fig. 4. January and July zonal contrail LW (uppermost dotted and solid lines), SW (lowermost dotted and solid lines), and net (middle dotted and solid lines) radiative forcings with natural clouds included (all sky) and excluded (clear sky). The numbers show the global average in $mW\,m^{-2}$.

ACPD
11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

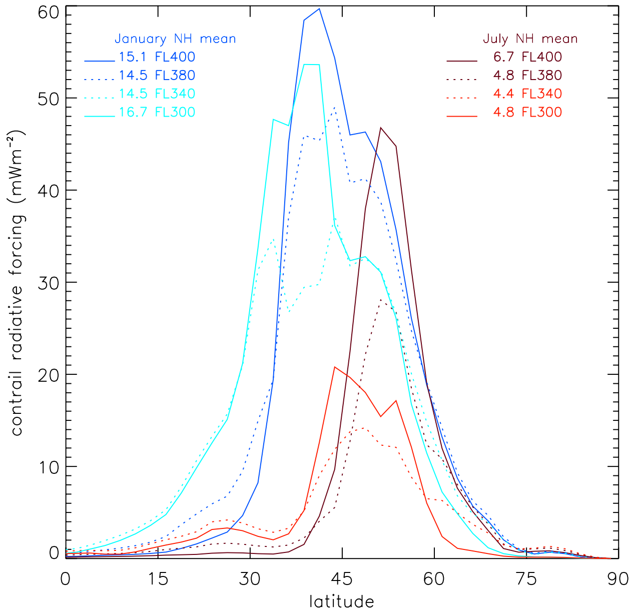

Fig. 5. January and July zonal mean contrail net RFs for cruise altitudes of 30 000, 34 000 and 38 000 ft (FL300, FL340 and FL380, respectively). The numbers show the NH average in mW m^{-2}.

ACPD
11, 19927–19952, 2011

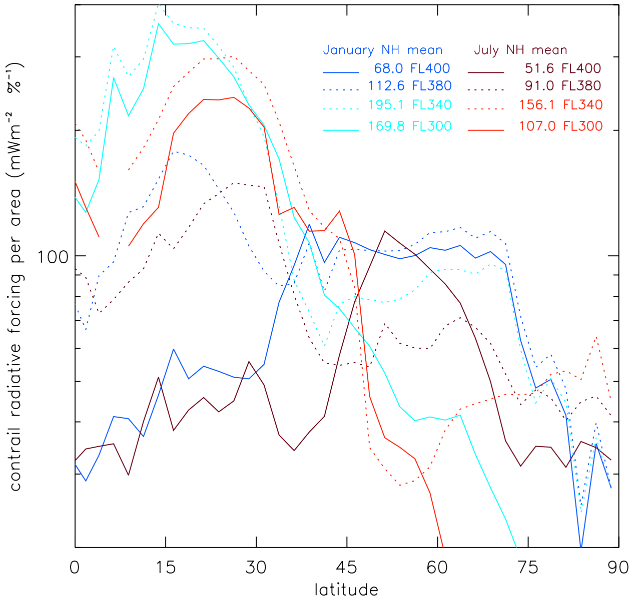

Fig. 6. Same as Fig. 5 per unit contrail cover (in %).

ACPD
11, 19927–19952, 2011

Sensitivity of persistent contrail radiative properties

R. R. De León et al.

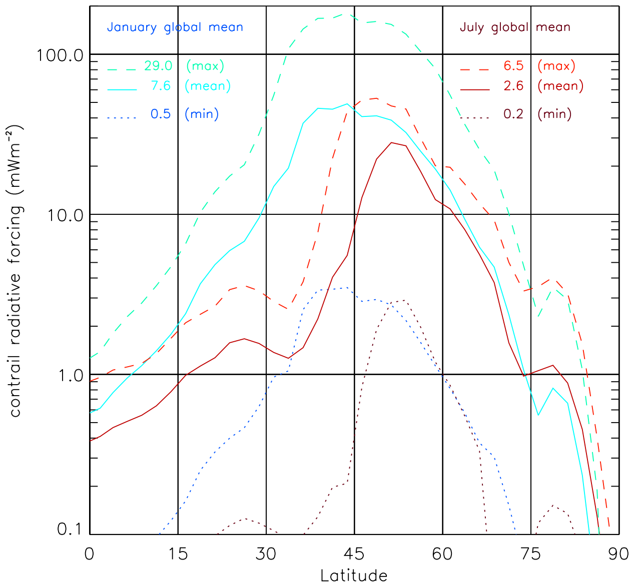

Fig. 7. January and July zonal contrail net radiative forcing for mean, minimum (min), and maximum (max) IWC assumptions at FL380. The numbers show the global average in $mW\,m^{-2}$.

ACPD
11, 19927–19952, 2011