GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 8, 10.1029/2001GL014075, 2002

Towards a reliable GCM estimation of contrail radiative forcing

Susanne Marquart and Bernhard Mayer

Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

Received 14 September 2001; revised 4 March 2002; accepted 4 March 2002; published 17 April 2002.

[1] Selected results of the ECHAM4 general circulation model are compared with sophisticated radiative transfer model calculations in order to investigate the performance of the ECHAM4 radiation schemes with respect to the radiative forcing (RF) of contrails. The mean shortwave RF is found to be in accordance with radiative transfer model results. For the longwave part it is shown that the effective emissivity approach combined with the assumption of maximum-random cloud overlap used in the standard ECHAM4 leads to a considerable underestimation of the longwave contrail RF. Hence, this approach cannot be recommended for calculating the longwave RF of optically thin clouds in general. As an alternative, more adequate results of a modified version of the ECHAM4 longwave scheme are discussed. *INDEX TERMS:* 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 1610 Global Change: Atmosphere (0315, 0325); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry

1. Introduction

[2] Contrails and other anthropogenic changes in cirrus cloudiness may have a significant influence on the Earth's climate system [*Fahey and Schumann*, 1999]. However, even the radiative forcing (RF) of line–shaped contrails is still quite uncertain. The estimates for global or regional contrail RF differ considerably [e.g., *Minnis et al.*, 1999; *Ponater et al.*, 2002; *Meyer et al.*, 2002].

[3] Recently, *Ponater et al.* [2002] presented the first parameterisation for line–shaped contrails in a general circulation model (GCM). Compared to mere radiative transfer model studies their approach has the conceptual advantage that it is possible to pay regard to the variability of contrail properties dependent on the actual ambient condition. On the other hand, the reliability of the GCM results is weakened by possible systematic errors in the model climatology and by its highly simplified radiative transfer schemes. As the estimate for net contrail RF given in the reference experiment of *Ponater et al.* [2002] is nearly two orders of magnitude smaller than the best estimate of IPCC [*Prather and Sausen*, 1999], it is neccessary to investigate the performance of the radiation scheme of their model with respect to contrails.

[4] For that purpose, we compare selected ECHAM4 GCM results (using the same model version as *Ponater et al.* [2002]) with calculations of a sophisticated radiative transfer model. This is a further step towards a more reliable estimate of contrail RF by a GCM and, at the same time, an evaluation of the ECHAM4 radiative transfer scheme with respect to optically thin clouds in general.

2. Models and Simulations

[5] We use the ECHAM4 GCM [*Roeckner et al.*, 1996] in a vertical resolution of 39 layers [*Land et al.*, 1999] and a horizontal spectral T30 resolution with a time step of 30 minutes. The model has been extended by a contrail parameterisation scheme which is based on the thermodynamic theory of contrail formation (see *Ponater et al.* [2002] for details). The RF of contrails is determined as the difference of radiative fluxes with and without contrails. The radiative transfer in ECHAM4 follows the parameterisations of *Fouquart and Bonnel* [1980] for the shortwave (SW) and *Morcrette* [1989] for the longwave (LW) part of the spectrum. In the SW, two spectral intervals are considered while the LW spectrum is divided into six spectral regions. Cloud (and contrail) parameters entering the SW radiative transfer calculations are coverage, optical depth, single scattering albedo, and asymmetry parameter, the radiative properties of both water droplets and ice crystals being derived from Mie theory. In order to account for the non-sphericity of ice particles, the respective asymmetry parameter is empirically reduced by a factor of 0.91 in the standard model [*Roeckner*, 1995]. The LW radiative transfer is calculated using the so-called effective emissivity approach (EEA), where an effective cloud cover is defined as the product of true coverage c and emissivity ϵ in each layer. For contiguous cloud layers maximum overlap is assumed and random overlap otherwise (maximum–random overlap assumption: MRO). In addition to the standard ECHAM4 scheme we test a modified version of its LW radiation code as proposed by *Räisänen* [1998].

[6] As reference radiative transfer model we use the LibRadtran model [*Kylling and Mayer*, 2001] with a numerical two–stream method [*Kylling et al.*, 1995]. The correlated-k parameterization by *Fu and Liou* [1992] with 6 bands in the SW and 12 bands in the LW is used. Scattering and absorption by molecules, cloud droplets, and ice particels are treated in full detail. As the focus of our comparison is the radiative transfer rather than the representation of cloud structure in climate models, LibRadtran was set up to mimic the geometric cloud representation of ECHAM4 as closely as possible: Clouds are arranged according to the MRO and then the radiative transfer calculation is done in independent pixel approximation, where the cloud field is split into individual (horizontally constant) columns and the radiation field is calculated as weighted average over the two–stream model results for each column. For complex cases with many cloud layers, several thousand individual runs were necessary to obtain a single result. Profiles of pressure, temperature, and water vapour as well as the cloud properties (coverage, liquid and ice water content, effective radii) were taken from the output of the climate model for each time step. Hence, the atmospheric environment and the respective cloud and contrail properties were identical for the two models. Water and ice cloud single scattering properties were calculated from the microphysical properties using Mie theory. For a fair comparison of the radiation schemes, the shape of ice particles was assumed to be non–spherical according to the treatment in ECHAM4 [*Roeckner*, 1995].

[7] The comparison was done for every two hours over one model year for one selected grid point in western Europe. This amounts to more than 4,000 individual data points comprising a high variability of atmospheric conditions. The chosen grid point is characterized by high air traffic density and therefore high contrail frequency. Table 1 lists the different ECHAM4 and LibRadtran case studies, as well as the notations used in the following sections.

0094-8276/02/2001GL014075$05.00

Table 1. Characteristics of the Radiative Transfer Calculations Performed with ECHAM4 and LibRadtran Two-stream

	ECHAM4	LibRadtran
LW	(E1-LW) EEA + MRO (standard ECHAM4) (E2-LW) EEA + modification (*Räisänen* [1998])	(L1-LW) MRO (reference) (L2-LW) EEA + MRO (L3-LW) no scattering, MRO
SW	(E-SW) non–spherical particles	(L-SW) non-spherical particles

[8] In order to further test the validity of our reference radiative transfer model, we compared the two–stream solution with DISORT results for a small subset of the time series. DISORT [*Stamnes et al.*, 1988], which is also implemented in LibRadtran, solves the equation of radiative transfer exactly, but requires much more computational time. The deviation of the two-stream RF from the DISORT solution was found to be only about 10%. In addition, a comparison of the SW RF calculated with the *Fu and Liou* [1992] band model with the *Kato et al.* [1999] parameterization which uses as much as 32 bands throughout the SW range, shows an agreement of better than 5%. These findings justify the use of the much faster two–stream solution in combination with the *Fu and Liou* [1992] band parameterization.

[9] Please note that the focus of this study is the evaluation of the one-dimensional ECHAM4 radiation scheme in comparison to an accurate one-dimensional radiative transfer model. The validity of the assumptions about the cloud field (the MRO and the assumption of horizontal homogeneity) as well as the applicability of the independent pixel approximation are not tested here. While they definitely contribute to the uncertainty of the RF calculations, these points are subject of current international research and far beyond the scope of this paper.

3. Results and Discussion

[10] Figure 1 shows the comparison of the LW and SW RF of contrails at the top of the atmosphere as calculated by ECHAM4 and LibRadtran. Figure 1a reveals large differences between both models for the LW part: The contrail RF calculated with the standard version of the ECHAM4 radiation scheme (E1-LW) is less than 50% of the LibRadtran reference calculation (L1-LW). For the SW RF (Figure 1b), the agreement between ECHAM4 and LibRadtran is good in a statistical sense, i.e., the systematic difference between both models is smaller than 5%. Nevertheless, the discrepancy can be quite large for individual cases – probably due to the highly simplified radiative transfer scheme in ECHAM4. As GCM studies generally focus on long-term means, it can be concluded that the uncertainty in the SW contrail RF due to the radiative transfer calculations themselves is much smaller than uncertainties e.g. arising from insufficiently known microphysical contrail properties such as particle shape or size.

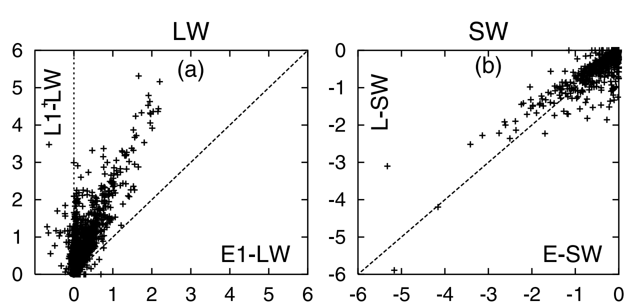

Figure 1. Comparison of LW and SW contrail RF (in W/m^2) as determined by the standard ECHAM4 and LibRadtran reference. (a) LW: E1-LW vs. L1-LW; (b) SW: E-SW vs. L-SW.

[11] In the following, we concentrate on the LW RF in order to investigate the reason for the large discrepancy between the two models. As a first test, we introduce the EEA also into LibRadtran (L2-LW), which makes both models agree almost perfectly (Figure 2b). This clearly identifies the EEA as the origin of the difference between ECHAM4 and LibRadtran.

[12] The reason for the systematic underestimation caused by the EEA/MRO combination can be understood as follows: In the EEA, the 'effective' cloud (or contrail) can be imagined as an opaque, 'black' cloud (i.e., emissivity $\epsilon = 1$) with coverage $c \cdot \epsilon$, in contrast to the real situation of a semi–transparent cloud with coverage c and emissivity ϵ. In the simple case of contrails in only one model layer with no adjacent natural clouds, the two approaches yield about the same results, at least if scattering is neglected. However, as soon as clouds or other contrails are present in layers immediately below or above the considered contrail layer, the situation changes. For simplicity, consider a single cloud layer directly above the contrail layer. Due to the MRO, the cloud overlaps maximally with the contrail (Figure 3). While in case of semi–transparent clouds the contrail's LW emission partly reaches the top of the atmosphere, the contrail does not contribute to the LW RF at the top in case of black, non–transparent clouds. As a situation with contrails in the vicinity of natural cirrus or other contrails is a common feature, the mean contrail LW RF is underestimated by ECHAM4, employing the EEA/MRO combination.

[13] An especially deficient case occurs when contrails form in an otherwise cloudless layer between two layers containing natural clouds (Figure 4): Whereas without contrails, the two cloud layers overlap randomly (as there is a cloud–free layer in–between), the overlap changes, if contrails are present, partly (i.e., for that part of the cloud column with the contrail in–between) to maximum

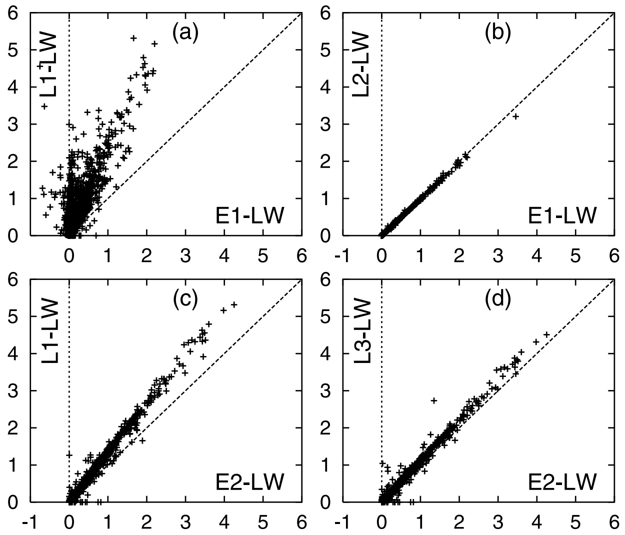

Figure 2. Comparison of LW contrail RF (in W/m^2) as determined by different model versions of ECHAM4 and LibRadtran. (a) E1-LW vs. L1-LW (equal to Figure 1a); (b) E1-LW vs. L2-LW; (c) E2-LW vs. L1-LW; (d) E2-LW vs. L3-LW.

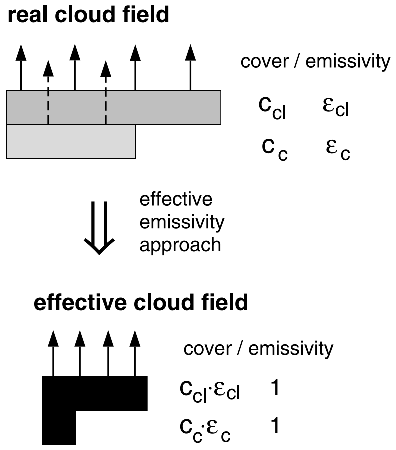

Figure 3. Schematic example showing why the EEA/MRO combination may lead to underestimation of the RF of optically thin clouds. Contrails underlying adjacent natural clouds are radiatively inactive in case of the EEA. The arrows symbolise upward emitted radiation.

overlap. Combined with the EEA, this constellation can even lead to an artificially negative LW contrail RF (examples are indeed evident in Figure 2a) because not only the contrail is radiatively inactive but also the part of the cloud overlapping maximally with the non–transparent contrail.

[14] From Figure 2a it can be deduced that for the data set underlying the present study the mean LW contrail RF is underestimated by as much as 70% when using the EEA/MRO combination. To reduce the systematic error in the ECHAM4 LW radiation scheme without major changes in the radiative transfer calclulation itself, the MRO has to be changed in a way that allows to consider the effects of coverage and emissivity separately in order to avoid undesirable invisibility effects. In this study, we adopt a method developed by *Räisänen* [1998] for the European Centre for Medium–Range Weather Forcasts LW scheme: True coverage and emissivity are used separately to calculate more appropriate weight factors for the combination of radiative fluxes for single overcast black cloud layers. As shown in Figure 2c, this modification improves the agreement with the LibRadtran reference calculation significantly. Note that the erroneous negative LW RF values are eliminated. Compared to the standard ECHAM4 result, the mean LW RF is increased by a factor of 2.5. Nevertheless, a systematic deviation to the LibRadtran reference calculation of about 25% still remains. This remaining underestimation is mainly due to the negligance of LW scattering by ECHAM4, as the comparison with LibRadtran without scattering (L3-LW) shows (Figure 2d). While in the LW range scattering might be neglected for optically thick clouds, it is clearly important for optically thin ice clouds.

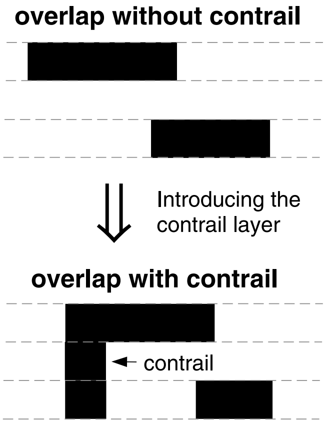

Figure 4. Schematic example showing why the MRO may lead to negative contrail RF, when using the EEA. Introducing contrails in an otherwise cloudless layer between two cirrus layers changes the overlap conditions in the model.

Table 2. Globally and Annually Averaged Contrail RF at the Top of the Atmosphere (in mW/m^2) (1) According to the Reference Experiment of *Ponater et al.* [2002] and (2) Repeating (1) Using the Modification of the ECHAM4 LW Scheme According to *Räisänen* [1998]

	Longwave	Shortwave	Net
(1)	2.0	−1.8	0.2
(2)	5.0	−1.8	3.2

4. Conclusions

[15] The comparison of ECHAM4 GCM simulations regarding the RF of contrails with sophisticated radiative transfer model calculations shows that the LW contrail RF is considerably underestimated when using the standard ECHAM4 approach of combined EEA/MRO, while the mean SW contrail RF is well represented by ECHAM4. As the LW and the SW contrail effects are similar in magnitude but different in sign, errors or uncertainties either in the LW or SW part of the spectrum may have a strong impact on net contrail RF. For example, for the reference experiment of *Ponater et al.* [2002], the compensation of LW and SW effects is excessive, because the LW RF is underestimated in the standard ECHAM4 LW scheme. Repeating their contrail RF estimation using the modification of *Räisänen* [1998] in the LW scheme leads to an increase in global mean LW RF at the top of the atmosphere by a factor of 2.5 (Table 2), which comes very close to the result for the single grid point considered above. At the same time, global mean net contrail RF increases from 0.2 to 3.2 mW/m^2, i.e., more than one order of magnitude. The net RF may even be higher if LW scattering would be accounted for.

[16] In general, it should be emphasized that the underestimation of LW RF when using the EEA/MRO combination is not restricted to artificially introduced thin ice-clouds such as contrails. Rather it also concerns natural clouds, whose optical depth is small enough (smaller than about 3) to give a distinct difference between true and effective cloud cover. Therefore, the EEA/MRO combination must be regarded as inadequate to quantify the radiative effect of optically thin clouds.

[17] **Acknowledgments.** The authors are grateful to P. Räisänen, who kindly provided the method for the modification of the ECMWF longwave scheme. Special thanks goes to M. Ponater for helpful discussions. The first author has received support from the “Studienstiftung des deutschen Volkes”. Part of this work was funded by the EU project “Tradeoff”.

References

Fahey, D. W., and U. Schumann, Aviation-produced aerosols and cloudiness, *IPCC special report ‘Aviation and the Global Atmosphere’*, 65–120, Cambridge Univ. Press, New York, 1999.

Fouquart, Y., and B. Bonnel, Computations of solar heating of the Earth’s atmosphere: a new parameterization, *Beitr. Phys. Atmos.*, *53*, 35–62, 1980.

Fu, Q., and K. Liou, On the correlated k-distribution method for radiative transfer in nonhomogeneous atmospheres, *Journal of the Atmospheric Sciences*, *49*, 2139–2156, 1992.

Kato, S., T. Ackerman, J. Mather, and E. Clothiaux, The k-distribution method and correlated-k approximation for a shortwave radiative transfer model, *J. Quant. Spectrosc. Radiat. Transfer*, *62*, 109–121, 1999.

Kylling, A., and B. Mayer, LibRadtran, a package for radiative transfer calculations in the ultraviolet, visible, and infrared, http://www.libradtran.org, 1993–2001.

Kylling, A., K. Stamnes, and S.-C. Tsay, A reliable and efficient two-stream algorithm for spherical radiative transfer: documentation of accuracy in realistic layered media, *Journal of Atmospheric Chemistry*, *21*, 115–150, 1995.

Land, C., M. Ponater, R. Sausen, and E. Roeckner, The ECHAM4.L39(DLR) atmosphere GCM — Technical description and model climatology, *DLR-Forschungsbericht 1999–31*, 45 pp., ISSN 1434-8454, Köln, Germany, 1999.

Meyer, R., H. Mannstein, R. Meerkötter, U. Schumann, and P. Wendling, Regional radiative forcing by line-shaped contrails derived from satellite data, *J. Geophys. Res.*, in press, 2002.

Minnis, P., U. Schumann, D. R. Doelling, K. M. Gierens, and D. Fahey, Global distribution of contrail radiative forcing, *Geophys. Res. Lett.*, *26*, 1853–1856, 1999.

Morcrette, J.-J., Description of the radiation scheme in the ECMWF model, ECMWF Tech. Memo. 165, Research Department ECMWF, 26 pp., Reading, UK, 1989.

Ponater, M., S. Marquart, and R. Sausen, Contrails in a comprehensive global climate model: parameterisation and radiative forcing results, *J. Geophys. Res.*, in press, 2002.

Prather, M., and R. Sausen, Potential climate change from aviation, *IPCC special report 'Aviation and the Global Atmosphere'*, 185–215, Cambridge Univ. Press, New York, 1999.

Räisänen, P., Effective longwave cloud fraction and maximum-random overlap of clouds: a problem and a solution, *Mon. Wea. Rev.*, *126*, 3336–3340, 1998.

Roeckner, E., Parameterization of cloud radiative properties in the ECHAM4 model, *Proceedings of the workshop "Cloud microphysics parametrizations in global circulation models"*, *WCRP-90*, 105–116, Kananaskis, Canada, 1995.

Roeckner, E., et al., The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate, *Max-Planck-Institut für Meteorologie*, *Rep. 218*, 90 pp., ISSN 0937-1060, Hamburg, Germany, 1996.

Stamnes, K., S. Tsay, W. Wiscombe, and K. Jayaweera, A numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media, *Applied Optics*, *27*, 2502–2509, 1988.

S. Marquart and B. Mayer, DLR, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Postfach 1116, D-82234 Wessling, Germany. (Susanne.Marquart@dlr.de; Bernhard.Mayer@dlr.de)