Importance of representing optical depth variability for estimates of global line-shaped contrail radiative forcing

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Estimates of the global radiative forcing by line-shaped contrails differ mainly due to the large uncertainty in contrail optical depth. Most contrails are optically thin so that their radiative forcing is roughly proportional to their optical depth and increases with contrail coverage. In recent assessments, the best estimate of mean contrail radiative forcing was significantly reduced, because global climate model simulations pointed at lower optical depth values than earlier studies. We revise these estimates by comparing the probability distribution of contrail optical depth diagnosed with a climate model with the distribution derived from a microphysical, cloud-scale model constrained by satellite observations over the United States. By assuming that the optical depth distribution from the cloud model is more realistic than that from the climate model, and by taking the difference between the observed and simulated optical depth over the United States as globally representative, we quantify uncertainties in the climate model's diagnostic contrail parameterization. Revising the climate model results accordingly increases the global mean radiative forcing estimate for line-shaped contrails by a factor of 3.3, from 3.5 mW/m^2 to 11.6 mW/m^2 for the year 1992. Furthermore, the satellite observations and the cloud model point at higher global mean optical depth of detectable contrails than often assumed in radiative transfer (off-line) studies. Therefore, we correct estimates of contrail radiative forcing from off-line studies as well. We suggest that the global net radiative forcing of line-shaped persistent contrails is in the range 8–20 mW/m^2 for the air traffic in the year 2000.

aviation | global change

Persistent contrails form in ice supersaturated areas at cold temperatures (< −40 °C) as narrow, line-shaped ice clouds behind cruising aircraft and transform into extended, irregularly shaped cirrus clouds. Here, we use the term "contrails" as a synonym for "line-shaped persistent contrails," of which some have a sufficiently large optical depth to be detectable in satellite imagery. The term "contrail cirrus" is used to denote contrails of all kinds of shapes and ages covering their entire life cycle. The associated cloudiness changes are an important component of aviation-induced radiative forcing.

The global modeling of the contrail cirrus climate impact remains an elusive task due to their small-scale nature and longevity, as well as due to the general difficulty of representing ice supersaturation and natural cirrus in models of coarse spatial resolution (1). A number of issues arise when comparing predicted and observed contrail cirrus coverage, including the specification of the mean age of the subset of contrail cirrus detectable by satellites using passive space-borne remote sensing methods and their optical depth detection thresholds (2).

Attempts to quantify spatial coverage and radiative properties of contrails have been reported for about two decades (3). Among those variables, optical properties are the least known, and optical depth is regarded to be a major source of uncertainty for the contrail radiative forcing (RF). Passive satellite sensors have difficulties retrieving thin high ice clouds with solar optical depths $\tau < 0.1$–0.4 (4). In satellite observations, only contrails with lengths >10 km, widths >1–2 km, and $\tau > 0.5$ are easily observable, and many environmental factors affect their detectability (5). A recent microphysical model study (6) concluded that satellite observations (7) detected only about one-third of contrails over the United States, in the majority those with an optical depth above 0.05.

A number of studies estimated global contrail RF with radiative transfer models (off-line), using constant optical depth (8–10). A global climate model was employed to compute temporally and geographically varying coverage, optical depth, and RF of contrails online (11, 12). To this end, contrail formation probability (potential contrail coverage folded with a measure of air traffic density) was diagnosed in the climate model as a proxy for contrail coverage. The fraction of contrail coverage deemed visible was then calibrated to an observational estimate of contrail coverage from satellite data in a specific region. A globally constant calibration factor is applied for this purpose. This calibration method, originally developed to diagnose contrail coverage (13), depends crucially on assumptions about the detectability of contrails in satellite observations, as we demonstrate in the present work. The meteorological variables controlling contrail coverage and optical depth vary strongly regionally. Therefore, methods that rely on constant calibration factors or constant optical depth values are physically questionable. Furthermore, contrail cirrus cannot be simulated using such methods (1, 2).

The downscaling of the global contrail RF estimate from 20 mW/m^2 for the year 1992 to 10 mW/m^2 for 2005 by the Intergovernmental Panel of Climate Change (IPCC) (14, 15) was based in part on results from the climate model discussed below. By combining recent observational and modeling evidence regarding contrail optical depth and its variability, we investigate and quantify two independent sources of error in the previous climate model simulations: The first one is tied to the calibration method given that only a part of the optical depth distribution is detectable, and the second one addresses a potential, systematic low bias in the simulated optical depth. By additionally correcting radiative transfer studies for prescribing a too low global mean (constant) optical depth, we are able to provide a representative range for the global contrail RF.

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Observations and Models

Cloud Model. Contrail cirrus coverage and microphysical properties are controlled by depositional growth and sedimentation of ice particles, and vertical wind shear-induced horizontal spreading in ice supersaturated layers. We created and validated a microphysical, cloud-scale model (CCSIM) that solves the equations for these processes analytically in two-dimensional

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calculations of contrail evolution (6). We further defined probability distribution functions (PDFs) of the cloud-controlling factors (temperature, ice supersaturation, wind shear, and supersaturated layer depth), covering a wide range of environmental states that affect the development of young contrails (young relative to their possible lifetime of a day or more). The resulting large samples of contrail properties, optical depth, and several microphysical variables were statistically analyzed with contrail life times limited to 4 h past formation. This means CCSIM simulates the younger contrails that are most likely still line-shaped and are therefore comparable to those detected by satellite sensors. However, CCSIM simulates contrails of all optical depths, including those not detectable by satellites.

Satellite Observations. Monthly contrail optical depth statistics for the year 2001 were derived over the United States, applying an automated contrail detection algorithm to infrared radiances measured by the Advanced Very High Resolution Radiometer (AVHRR) and correcting the coverages subjectively (7). CCSIM was employed to analyze and interpret these satellite observations. To constrain the prescribed PDF shapes of the cloud-controlling factors in CCSIM, yearly mean values and spreads of temperature and wind shear distributions were estimated from regional numerical weather analyses (monthly mean data) for the times the satellite observations were made. These represent rather warm conditions with low mean shear, but large variability in both quantities. The parameters of the PDFs of ice supersaturation and supersaturated layer depth were estimated from aircraft and radiosonde data taken at different locations. Contrail optical depth and other parameters were sampled in proportion to the contrail width, similar to the satellite observations. We refer to ref. 6 for a detailed description of this approach.

The variability of the input parameters results in variability of contrail optical depth shown alongside the cumulative distribution in Fig. 1*A* (see also Table 1). The distribution is very broad, with the standard deviation dramatically exceeding the mean value, $\tau_m = 0.125$. A large number of weakly supersaturated events together with large shear values generate many optically thin contrails, as indicated by the low median value, $\tau_{\text{med}} = 0.02$. The corresponding large fraction of subvisible cases ($\tau \leq 0.02$, not visible by ground-based human observers, 16) is 50%. Nevertheless, a significant amount of optically thicker ($\tau > 0.3$) contrails exists, reaching almost 10%. The mean optical depth from the observed PDF is $\tau_m = 0.26$ when neglecting contrails with $\tau > 1$ (7). The mean value of the PDF from CCSIM excluding the undetected contrails, also excluding cases with $\tau > 1$, is $\tau_m = 0.28$, in good agreement with the satellite data. The mean value of the simulated distribution covering all optical depths (Fig. 1*A*) is much lower, $\tau_m = 0.125$, because of the inclusion of many optically very thin cases.

The comparison of the PDF(τ) from CCSIM with the observed annual mean statistic pointed at a significant undersampling of optically thin contrails by the satellite observations (6). Empirical detection efficiencies were derived as the fraction of simulated contrail events that were actually observed as a function of τ in order to account for the undetected portion. The satellite measurements detected only ~65% of the total coverage of contrails of all optical depths. Contrails that were optically thinner than $\tau = 0.05$ were detected with a probability of only 11%. Application of the calibration method requires a single detection threshold, τ_{det}, below (above) which the detection efficiency is 0 (1). We determine from the cumulative PDF (Fig. 1*A*), for conditions over the United States in 2001, the value above which the optical depths of 65% of all contrails lie. This value, $\tau = 0.05$, we use later on as the revised optical depth threshold, τ_{det}, for our climate model studies.

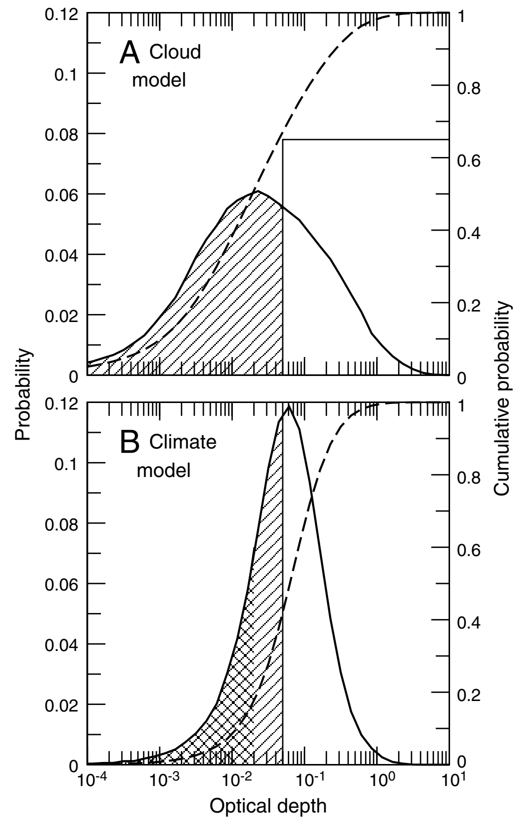

Fig. 1. Probability distributions of optical depth, τ, at solar wavelengths (solid curves) and corresponding cumulative distributions (dashed curves). (*A*) Annual average result for contrails with 4-h lifetime simulated with the cloud-scale model CCSIM and constrained by meteorological conditions at 250 hPa representative for the continental United States (128W-67W, 28N-54N) in the year 2001 (6). (*B*) Annual average result from multiyear simulations of diagnostic contrails over the same region and at the same pressure level using the global climate model ECHAM from ref. 12. Contrary to ECHAM, CCSIM is incapable of simulating regional fractional coverage, because it resolves only one contrail at a time. All of our discussions related to the optical depth distributions are independent of coverage.

Global Climate Model. We revise the contrail optical depth estimates from the European Center model/Hamburg version (ECHAM) climate model (12). In these simulations, global coverage was calculated based on an emission inventory representing the year 1992 and on the parameterized potential contrail coverage (11). The resulting geographical distribution of contrail coverage, using random overlap of contrails, was calibrated to satellite measurements over parts of Europe and the eastern North Atlantic (17). These satellite data were compiled from the time periods 1979–1982 and 1989–1992. The calibration factor derived for this area was assumed to be temporally and spatially constant in ECHAM in order to calculate the actual global coverage. In the calibration step, it was assumed (11) that line-shaped contrails provided by ref. 17 were detected above the visibility threshold, $\tau_{\text{vis}} = \tau_{\text{det}} = 0.02$. This choice to calibrate contrail coverage in ECHAM was deliberately made in the absence of information on the optical depth distribution and underlying satellite detection efficiencies. The parameterization implies that the detection efficiency is 1 above and 0 below the chosen optical depth threshold (see above). Coverage, optical depth, and RF inferred by the parameterization are temporally and geographically variable. Therefore, in case of a recalibration, the total contrail coverage and RF increase, but the contrail optical properties do not change. Optical depth in ECHAM is based on the simulated contrail ice water path and effective radius, which are

Table 1. Integral properties of the optical depth distributions over the continental USA

Model	τ_m	σ^2	σ/τ_m	τ_{med}	$f(\tau > 0.02)$	$f(\tau > 0.05)$	$f(\tau > 0.3)$
CCSIM	0.125 (0.28)	0.11	2.6	0.020	0.50	0.35	0.10
ECHAM	0.094	0.02	1.5	0.065	0.82	0.57	0.08

Values taken at 250 hPa from the CCSIM cloud model (sample size ~100,000 equal to the number of different contrail forcing conditions) and the ECHAM climate model. Annual mean and median values are τ_m and τ_{med}, respectively, σ^2 is the PDF variance. Values f are integrals over the PDFs above a threshold, $\tau > 0.02$: fraction visible by ground-based observers; $\tau > 0.05$: fraction detectable in the satellite observations; $\tau > 0.3$: fraction of optically thicker cases. The τ_m value noted in brackets for CCSIM results from correcting for undetected contrails in the observation year 2001. The results for ECHAM were derived from simulating 17 y of diagnostic contrails.

diagnosed at each time step (30 min) from the moisture available for deposition on cloud ice in proportion to the contrail coverage.

We compare contrail optical depth simulated by ECHAM with that from CCSIM (Table 1). The ECHAM statistic over the continental United States (at 250 hPa, similar to CCSIM conditions and the observations) is based on 17 y of 1990s-climate simulations (Fig. 1*B*). ECHAM simulates a narrower distribution with smaller variance and a lower mean value, τ_m. The median optical depth is therefore closer to the mean, and the fraction of subvisible cases is smaller in ECHAM than in CCSIM. We additionally note that the interannual variability in τ_m obtained from ECHAM with a standard deviation of 0.004 is much smaller than the seasonal variability; monthly mean optical depths vary between a minimum of 0.052 (January value) and a maximum of 0.176 (August value). The cross-hatched and hatched areas under the PDF in Fig. 1*B* illustrate the fraction of undetected contrails that are excluded when calibrating the diagnosed contrail formation probability to the observed coverage, assuming either $\tau_{det} = 0.02$ or $\tau_{det} = 0.05$, respectively. For the calculations of RF in ECHAM, all contrails of all optical depths were included.

CCSIM is used to make comparisons between satellite observations and ECHAM results possible. As a tool to simulate the spatial and temporal evolution of many single contrails, CCSIM resolves more realistically the inhomogeneity in contrail properties and therefore is better at capturing the microphysical variability than a large-scale climate model. It therefore can be expected to produce a more reliable PDF(τ) than ECHAM, which is not designed to resolve single clouds or their microphysics. We identify several reasons why ECHAM underestimates the distribution variance relative to CCSIM. CCSIM captures the full spatial variability of contrail ice particle size spectra, whereas contrails in ECHAM have average optical properties. Furthermore, differences in the meteorological variables controlling the cloud properties between CCSIM and ECHAM as well as in the treatment of the ice microphysics between the two models may affect the distribution shape.

Results

We now discuss the consequences of our findings for assessment values of RF from the literature, which exist for various reference years within 1992–2005. We have mentioned that the diagnosed contrail coverage is dependent on the assumed detection threshold τ_{det} used for calibration. Any error in τ_{det} has large implications for the global RF determined by the climate model using the calibration method. Discussing the RF between 1992 and 2005, we consider only changes in air traffic density between two different years (1992 and 2000) and no climate change effects.

The value $\tau_{det} = \tau_{vis} = 0.02$ that was used in the original study (12) to calibrate the contrail coverage over Europe in ECHAM is significantly smaller than the value $\tau_{det} = 0.05$ estimated for the AVHRR observations over the United States using CCSIM (Fig. 1*A*). When assuming a higher detection threshold, the calibration method leads to larger global average contrail coverage. This is because the calibration factor must increase when a smaller fraction of simulated contrail coverage is assumed to be detectable. The resulting detectable contrail coverage is then adjusted to the contrail coverage inferred from regional satellite observations. The contrail optical depths calculated by ECHAM are not affected by the recalibration. How much an increase in τ_{det} enhances global contrail coverage and RF depends on the spread of the simulated contrail optical depth distribution and on the vertical overlap between contrails and natural clouds.

We performed ECHAM simulations using $\tau_{det} = 0.05$ instead of 0.02, again assuming that τ_{det} is globally representative. The recalibration applied to reproduce the observed contrail coverage (17) resulted in a large increase of the net global contrail RF by a factor 2.7, from 3.5 mW/m^2 (12) to 9.3 mW/m^2 for the year 1992 (see also Table 2). These RF values assume maximum random overlap of contrails and natural clouds and include an a posteriori correction of a known long-wave bias for high ice clouds of the model's radiation scheme (18). Note that ECHAM provides stratosphere-adjusted RF values according to the IPCC definition (19).

The second point we investigate concerns the difference in τ_m between CCSIM and ECHAM that amounts to 25%. This differ-

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Table 2. Estimates of global mean radiative forcing due to line-shaped persistent contrails

Reference year	Original estimate, mW/m^2	Corrected estimate, mW/m^2 (this study)	Method (diagnostic)	Original source
1992	3.5	9* / 12† / 20‡	GCM	(12)
1992	9	8† / 14‡	Off-line	(8)
2000	10 (6–15)§	17‡ (14–20)§	GCM and off-line	(20)
1992	2	6† / 8‡	Off-line	(9)
2002	6	11†	Off-line	(10)
1992	20		Off-line	(14)
2005	10		GCM and off-line	(15)
2005	11.8 (5.4–25.6)§		GCM and off-line	(22)

Values derived by various diagnostic methods for several reference years. The correction in the radiative transfer (off-line) model studies consists of using a constant optical depth value for detectable contrails only, consistent with the coverage of contrails detected in satellite imagery. The climate model estimate assumes a spatially and temporally variable distribution of contrail optical depths and is corrected for the calibration error and additionally for the potential low optical depth bias. All corrected estimates derived in our study are rounded values.

*Corrected for calibration error.

†Corrected for mean optical depth.

‡Extrapolated to air traffic in the year 2000.

§Minimum–maximum range.

ence is statistically highly significant (error probability well below 1%) according to a test statistic for two independent, normally distributed, random samples (20). If the difference between ECHAM and CCSIM results over the United States were globally representative, this would point to an underestimation of the global mean contrail optical depth of 25% by ECHAM. This figure applies approximately to RF as well, because most of the simulated contrails are optically thin. Correcting for this systematic low bias would further raise the RF value from 9.3 mW/m^2 to 11.6 mW/m^2. This potential bias is small compared to the uncertainty inherent in the calibration method due to the need of defining a $\tau_{\rm det}$-value. Both corrections lead to an overall increase of contrail RF by a factor of 3.3, from 3.5 mW/m^2 to 11.6 mW/m^2. This correction of RF crucially relies on the difference between ECHAM and CCSIM results over the United States being globally representative.

The original results for 1992 of ECHAM (12) and one early off-line study (8) were extrapolated in ref. 21 for air traffic in the year 2000, resulting in 6 mW/m^2 and 15 mW/m^2, respectively. This range was used to publish an arithmetic mean value of 10 mW/m^2 (21), which was adopted later by the IPCC (15). Our corrected figures for ECHAM, when scaled to aviation for the year 2000 as in ref. 21, are ∼16 mW/m^2 (after rounding) when accounting for the increased contrail detection threshold in the calibration method and ∼20 mW/m^2 when additionally correcting for the low bias in mean optical depth (Table 2).

Radiative forcing estimates from off-line studies (8–10) employed numerical weather reanalysis data to infer potential contrail coverage and calibrated to satellite-derived coverage over Europe (17). They estimated only the RF of the detectable contrails and assumed a constant global mean optical depth. Therefore, they do not suffer from the calibration problem attributed to the climate model simulations. However, the optical depth needs to be the mean value of detectable contrails only. In ref. 8, a value of 0.3 was employed. Assuming that the optical depth over the United States is representative for the global mean, this hints at a slight overestimation by a factor of $0.3/0.28 = 1.07$. Consequently, the RF value of detectable contrails should also be corrected, which leads to ∼14 mW/m^2, when scaled to 2000. Calculating the arithmetic mean of the results from refs. 12 and 8 as in ref. 21, but now with our corrected estimates, leads to a global mean net contrail RF of 17 mW/m^2. This corresponds to an increase of 70% relative to the latest IPCC recommendation of 10 mW/m^2 (15). Another off-line study (10) used an optical depth of 0.15, in which case our correction factor of $0.28/0.15 = 1.9$ leads to ∼11 mW/m^2 for 2002. The same procedure applied to the results of ref. 9 for their $\tau_m = 0.1$ case leads to a corrected value of 5.6 mW/m^2 (year 1992), which would increase to ∼8 mW/m^2 when extrapolated for 2000. In all these off-line studies it is not obvious how the missing contribution of undetected contrails to the global RF could be accounted for.

Our revised RF estimates, summarized in Table 2, rely on improved observational and microphysical constraints, combining the available knowledge on mean optical depth and variability. However, uncertainties in the climate model's diagnostic contrail parameterization, such as those related to the constant calibration factor and optical depth detection threshold, the cloud overlap assumptions, and the optical depth bias, remain.

As the calibration method has been used in many studies to estimate the global contrail RF, our quantification of the error associated with applications of this method in global climate model or off-line studies is key to assessing the contrail-climate impact in future work. More importantly, the critical analysis presented here reinforces the need for process-based model estimates of contrail coverage and optical properties that do not rely on the calibration of coverage, as well as a global homogeneous dataset of contrail coverage and optical depth. A process-based parameterization for contrail cirrus as a separate class of high clouds in ECHAM that does not rely on the calibration method and that is not restricted to line-shaped contrails has been introduced recently (2). This parameterization will be employed in studies of the global coverage and RF of contrail cirrus of any age and shape, which we expect to be much larger than that of contrails only.

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