Sensitivity of contrail cirrus radiative forcing to air traffic scheduling

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[1] Air traffic effects high cloudiness and therefore the Earth's radiation budget by producing contrail cirrus. Contrail cirrus comprise of line-shaped contrails and irregularly shaped ice clouds that originate from them. The warming effect of contrail cirrus is disproportionally large at night, since at daytime the cooling due to the short wave cloud albedo effect acts toward compensating the long wave warming effect. Therefore it has been suggested to restrict air traffic to daytime in order to reduce its climate impact. The potential for reducing the contrail cirrus radiative forcing by shifting air traffic to daytime depends on the diurnal cycle of contrail cirrus coverage which is in turn determined by the diurnal cycle of air traffic and the contrail cirrus lifetimes. Simulations with a global atmospheric general circulation model indicate that the annual mean contrail cirrus coverage may be almost constant over the day even in areas where air traffic is close to zero at night. A conceptual model describing the temporal evolution of contrail cirrus coverage reveals that this is due to the large variability in contrail cirrus lifetimes in combination with the spreading of contrail cirrus. This large variability of lifetimes is consistent with observational evidence but more observations are needed to constrain the contrail lifetime distribution. An idealized mitigation experiment, shifting nighttime flights to daytime, indicates that contrail cirrus radiative forcing is not significantly changed.

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1. Introduction

[2] The climate effect of aviation accounts for 2% to 14% of the total anthropogenic radiative forcing (RF) [*Lee et al.*, 2009]. Since air traffic is expected to rise significantly, with the number of airplanes almost doubling from ∼20,500 in 2002 to ∼40,500 in 2026 [*Airbus*, 2007], the climate impact of aviation will become an increasingly important factor. Contrail induced clouds, contrail cirrus, were estimated to be the largest single RF component connected with air traffic [*Burkhardt and Kärcher*, 2011]. They consist of young line-shaped contrails, that form in the wake of aircraft if the meteorological conditions are favorable [*Schumann*, 1996], and the irregularly shaped clouds that arise from them. When air is supersaturated with respect to ice, contrail cirrus can persist for many hours. Single contrails have been tracked for up to 17 hours in satellite images [*Minnis et al.*, 1998]. Another study showed that contrails over Central Europe occur preferentially in groups within areas of a few 100 km diameter, which can persist for more than one day [*Bakan et al.*, 1994]. During their life cycle many contrails lose their line-shape, transforming into cirrus-like clouds or cloud clusters that are not distinguishable from natural cirrus any longer. Such contrail-induced cirrus have been tracked for 18 hours covering more than 15.000 km^2 at their peak [*Haywood et al.*, 2009].

[3] Contrail cirrus are able to form and persist in air that is only weakly ice-supersaturated when the formation of natural cirrus is not possible, thus increasing total cloud coverage and changing the radiation budget. On the one hand, they warm the atmosphere by trapping outgoing terrestrial longwave radiation and, on the other hand, they cool by reflecting solar shortwave radiation. Whereas the longwave effect depends linearly on coverage and optical depth of optically thin contrail cirrus, the shortwave effect also depends on the solar zenith angle and is zero at night and largest during sunrise and sunset. The diurnal cycle of RF for an optically thin ice cloud was simulated by *Meerkötter et al.* [1999]. RF is maximum at night and smaller during the day, when longwave RF is partly compensated by the shortwave effect, with minima in the morning and in the evening. Therefore the net radiative impact of nighttime coverage is disproportionally large and it has been suggested to shift nighttime air traffic to daytime in order to reduce the climate effect of contrails [*Stuber et al.*, 2006], based on the analysis of line-shaped contrails. As long as contrails that are formed during the day mainly exist during the day, this could be a viable option.

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[4] *Stuber et al.* [2006] and *Stuber and Forster* [2007] could only simulate the diurnal cycle of line-shaped contrail coverage prescribing a fixed contrail lifetime of 2 hours. Contrail coverage was calculated based on a diagnostic parameterization and scaled to an observed coverage of line-shaped contrails as in *Ponater et al.* [2002], limiting contrails temporally and spatially to the areas and times of air traffic. *Burkhardt and Kärcher* [2009] developed a process-based contrail cirrus parameterization that does not rely on such a scaling and allows the simulation of the life cycle of contrail cirrus in the global atmospheric general circulation model (AGCM), ECHAM4. Ice supersaturation was parameterized and validated using observational data [*Burkhardt et al.*, 2008; *Lamquin et al.*, 2010]. Persistence, advection and spreading of contrails as well as their interaction with natural clouds are taken into account. Within this parameterization framework young contrails (defined as up to 5 hours old), which are assumed to represent the observed line-shaped contrails, constitute only a subset of those contrail cirrus. Coverage due to young contrails was validated using observational estimates of line shaped contrail coverage [*Burkhardt and Kärcher*, 2009]. Coverage of contrail cirrus and its properties are difficult to validate because contrail cirrus cannot, or only under special circumstances, be observed directly but may only be inferred from observations [e.g., *Boucher*, 1999; *Graf at al.*, 2009]. The RF associated with young contrails is estimated to be about nine times smaller than that from contrail cirrus of all ages [*Burkhardt and Kärcher*, 2011]. Furthermore, the lifetime of contrail cirrus clusters was found to depend strongly on the meteorological situation. In favorable conditions, that is in large ice-supersaturated areas, the lifetime of single contrail clusters and the associated contrail cirrus coverage was found to increase for many hours after air traffic has ceased [*Burkhardt and Kärcher*, 2009]. This means that the diurnal cycle of contrail cirrus coverage does not necessarily follow the diurnal cycle of air traffic but may rather be controlled by the synoptic situation. This provides a key motivation for our study.

[5] We examine the contribution of nighttime flights to contrail cirrus RF (Section 3), using the parameterization of *Burkhardt and Kärcher* [2009] and an hourly resolved flight data set. We discuss the daily variability of young contrail and contrail cirrus coverage and analyze the diurnal cycle using a conceptual model of contrail cirrus coverage inferring a probability distribution of contrail cirrus lifetimes (Section 4). Finally we present results from a mitigation experiment in order to quantify the reduction of contrail cirrus RF when shifting air traffic to daytime (Section 5).

2. Model and Data

[6] Two different approaches have been proposed in the literature in order to simulate contrail cirrus in a GCM. The first is to simulate contrail cirrus similarly to natural clouds, with fractional contrail coverage and contrail ice water content as prognostic variables (contrail fraction approach). The second is to simulate each individual contrail in the grid box of the GCM (individual contrail approach). The first method allows contrail cirrus to be simulated consistent with the subgrid scale variability inherent in the model's natural cloud scheme [*Burkhardt et al.*, 2008], calculating the part of the flight path that will form a contrail and assuming contrails within one grid box to be homogeneous [*Burkhardt and Kärcher*, 2009]. The individual contrail approaches [*Jacobson et al.*, 2011; *Schumann*, 2011] can resolve the location of a contrail if the flight path is known and advection is considered [*Schumann*, 2011]. (Assuming a low resolution model with a distance between Gaussian grid boxes of ∼270 km and a wind speed of 25 m/s a contrail is advected over the distance of one grid box within 3 hours, a lifetime that can be very often observed and is often exceeded.) The parameterization of *Jacobson et al.* [2011] resolves advection of contrails only once their spatial dimension has reached the grid scale, maximizing the overlap between contrails. Furthermore, spatial inhomogeneities within contrails may be resolved [*Jacobson et al.*, 2011] or contrails may be assumed to be homogeneous [*Schumann*, 2011]. In contrast to the contrail fraction approach, the individual contrail approaches do not consider variability in the background moisture field on the subgrid scale that might allow only part of the grid box to support or form a contrail. The parameterization of *Jacobson et al.* [2011] resolves the microphysics within the inhomogeneous contrail in detail, with the exception of contrail crystal sedimentation between grid cells that is disregarded. Using either method, it is of paramount importance to close the water budget in a way that does not favor either natural clouds or contrail cirrus when calculating the climate impact of contrail cirrus. Using a contrail fraction approach this has been realized [*Burkhardt and Kärcher*, 2009] by treating natural clouds and contrail cirrus on the same level of detail, with the parameterization of microphysical processes, advection and the large scale diffusion (parameterized as well as numerical) being the same for natural clouds and contrail cirrus, whereas this may pose a problem when simulating contrail cirrus in far more detail than natural clouds (e.g. treating contrails with no diffusion and natural clouds with diffusion would introduce an imbalance between the water budget terms of contrails and natural cirrus).

[7] We use the contrail fraction approach in order to simulate contrail cirrus. The atmospheric general circulation model ECHAM4/L39 [*Röckner et al.*, 1996; *Chen et al.*, 1996; *Land et al.*, 1999] has been applied atT30 resolution using a time step of 30 minutes. This corresponds to a horizontal distance between Gaussian grid boxes in 50°N of ∼270 km. The 39 vertical levels correspond to a resolution of about 700 m in the upper troposphere and lowermost stratosphere where contrails mainly form. Our contrail cirrus parameterization, CCMod, introduces a new prognostic cloud class, contrail cirrus [*Burkhardt and Kärcher*, 2009] in ECHAM4/L39. ECHAM4-CCMod is based on the parameterization of the physical processes determining a contrail's development capturing formation, persistence, advection and spreading of contrails. The parameterization consists of prognostic equations for the model variables fractional contrail cirrus coverage, contrail length and grid mean contrail cirrus ice water mass mixing ratio. Natural cloud and contrail cirrus microphysics and optical properties are parameterized as a function of water mass mixing ratio. Contrails and contrail cirrus are allowed to persist in those fractions of the grid box that are ice-supersaturated but cloud free [*Burkhardt et al.*, 2008]. In the model, natural cirrus and contrail cirrus can coexist in the same grid box, water vapor deposition on the contrail cirrus and natural cloud ice particles is proportional

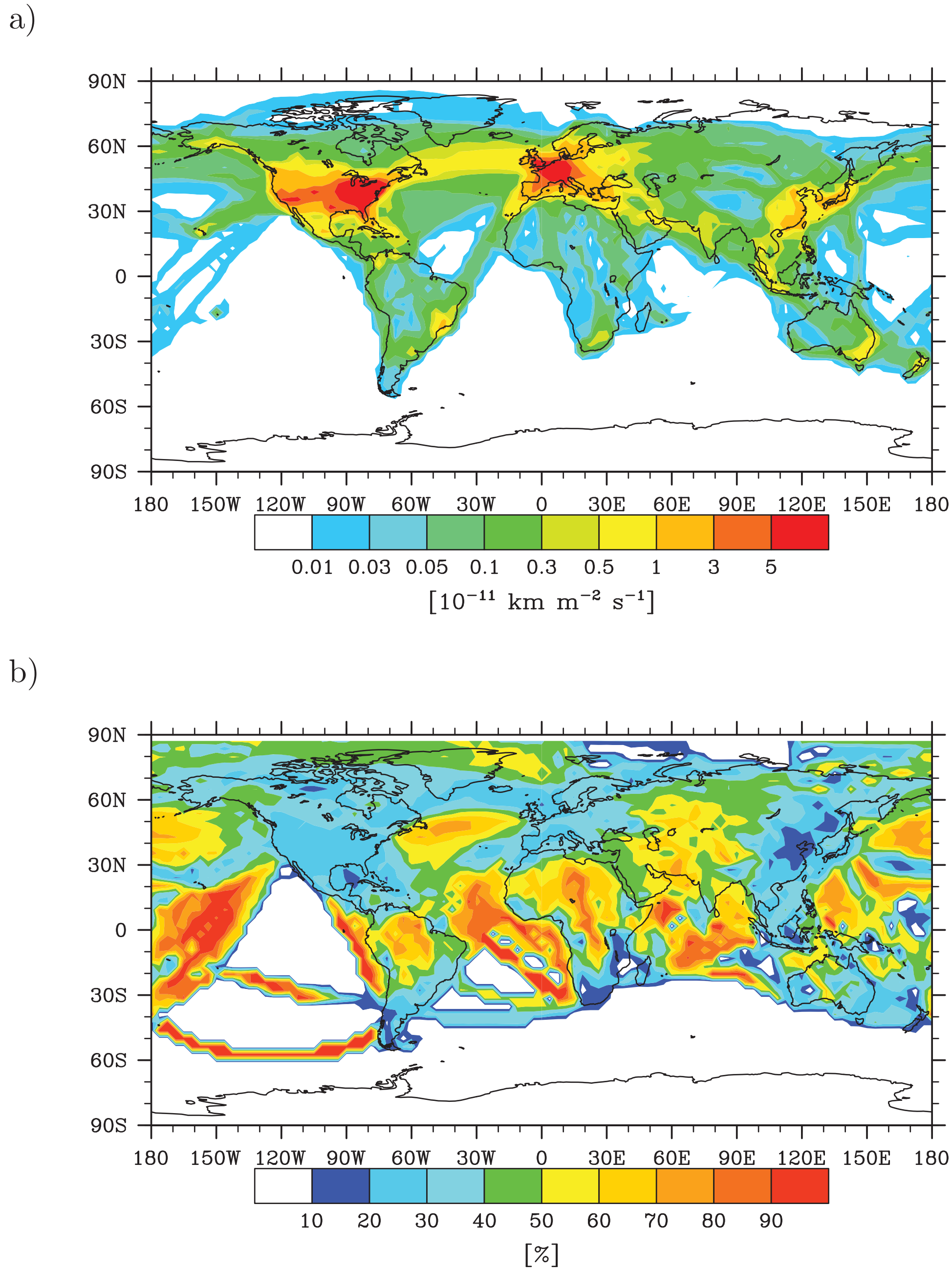

Figure 1. (a) Annual mean vertically integrated air traffic density and (b) annual mean contribution of nighttime air traffic to the total amount of air traffic according to the AERO2k flight inventory.

to the respective coverage. This means that natural clouds and contrail cirrus interact by competing for available water vapor. The stratosphere adjusted RF of contrail cirrus has been calculated online within ECHAM4-CCMod [*Burkhardt and Kärcher*, 2011] by calling the radiation scheme twice, one time with natural clouds and contrail cirrus and the other time without contrail cirrus.

[8] The validation of contrail cirrus coverage poses a problem due to the lack of a comprehensive data set of direct contrail cirrus observations. These do not exist because of difficulties distinguishing contrail cirrus from natural cirrus clouds in satellite images. Instead the parameterized ice-supersaturated areas, which serve as a constraint for contrail cirrus coverage, have been validated using observational data [*Burkhardt et al.*, 2008; *Lamquin et al.*, 2010]. Furthermore, the model's performance has been validated by comparing coverage caused by young contrails (up to 5 hours old) to statistics of line-shaped contrail coverage inferred from satellite data. The model was found to perform well when contrails with an optical depth above 0.02 or 0.05, representing the optical depth threshold for contrail detection, were considered [*Burkhardt and Kärcher*, 2009].

[9] Air traffic is prescribed by the gridded AERO2k flight inventory [*Eyers et al.*, 2004] for 2002. Annual total flight distances of civil aircraft were 17.9×10^9 nautical miles and water vapor emissions of civil and military aircraft were

Table 1. Contribution of Nighttime Air Traffic to Contrail Cirrus RF[a]

	Percentage of Nighttime Flights	Contribution of Nighttime Flights to Young Contrail RF	Contribution of Nighttime Flights to Contrail Cirrus RF	Approximate Contribution of Nighttime Flights to Contrail RF [*Stuber and Forster*, 2007]
Global Mean	31%	64% ± 1%	49% ± 1%	60%
USA	25%	54% ± 2%	45% ± 2%	55%
Western Europe	28%	63% ± 5%	50% ± 3%	60%
North Atlantic	61%	103% ± 7%	65% ± 5%	75%
Southeast Asia	35%	65% ± 3%	52% ± 4%	75%

[a]Annual mean contribution of nighttime flights to total air traffic, young contrail RF and contrail cirrus RF derived from a ten year simulation of ECHAM4-CCMod, prescribing air traffic with the AERO2k inventory and the contribution of nighttime flights to contrail RF derived by *Stuber and Forster* [2007] with the USA representing the area 130°W-65°W/55°N-25°N, Western Europe 10°W-20°E/55°N-40°N, the North Atlantic 45°W-10°W/55°N-45°N and Southeast Asia 90°E-140°E/20°S-20°N. The values of *Stuber and Forster* [2007] are estimated roughly from their Figure 5. For the contribution of nighttime flights to young contrail and contrail cirrus RF standard deviations are calculated from the yearly mean values.

217.1 Tg. We use a data set containing one week of hourly resolved data of water vapor emissions and flight kilometers for every second month of the year 2002. From this data set monthly mean diurnal cycles have been calculated. Diurnal cycles for the months, where no hourly resolved information was available, have been calculated by interpolating the mean diurnal cycles of the neighboring months.

[10] In the main air traffic regions of Western Europe and the USA 70% of aviation takes place (Figure 1a). The global mean vertically integrated air traffic density is larger at daytime (0.28×10^{-11} km/m^{2}s) than during the night (0.13×10^{-11} km/m^{2}s). The contribution of nighttime flights to the total amount of air traffic is 31% (Table 1). The geographical distribution of this contribution (Figure 1b) is in good agreement with the fraction of nighttime flights found by *Stuber and Forster* [2007], who used six hourly resolved AERO2k data and estimated nighttime flights to contribute 38% to total air traffic.

[11] An idealized flight inventory (AERO2k-id) has been created in order to test whether contrail cirrus RF can be reduced by banning nighttime flights. Nighttime flight kilometers and emissions were distributed evenly across the day, conserving the total amount of air traffic. North of 70°N and south of 70°S air traffic was left unchanged in polar nights. Since only 0.5% of total air traffic occurs at those times and places, this has only a small impact on the global mean results. Note that we did not shift individual flights but instead only grid mean flight kilometers and emissions. The new inventory therefore does not consist of realistic flight movements. The idealized experiment is rather meant to investigate whether this kind of mitigation has the potential of minimizing contrail cirrus RF at all.

[12] We conducted two fifteen year model runs with ECHAM4-CCMod, prescribing air traffic using different data sets: the realistic flight scenario (AERO2k) and the idealized flight inventory shifting all the air traffic to daytime while conserving the absolute amount of air traffic (AERO2k-id). We analyze flight kilometers, contrail cirrus coverage (using a maximum random overlap scheme) and contrail cirrus RF for day and night separately. From the AERO2k and the AERO2k-id experiments we estimate the effect of the mitigation experiment. Changes between the two experiments have been tested for significance using monthly mean data taking serial correlation within the time series into account [*Wilks*, 1995]. A simulation using an inventory containing only nighttime flights without conserving the total amount of air traffic (AERO2k-night) was run for ten years. We calculate the mean contribution of nighttime air traffic to contrail cirrus RF and its standard deviation from the AERO2k and the AERO2k-night experiments and compare to the *Stuber and Forster* [2007] values. We rerun five years of the AERO2k and the AERO2k-id experiment with hourly resolved diagnostics (the archiving interval of the standard runs is 12 hours), to discuss the diurnal cycle of variables that are relevant for contrail cirrus development.

3. Radiative Forcing of Nighttime Flights

[13] Prescribing air traffic for the year 2002 (AERO2k) in ECHAM4-CCMod, monthly and global mean contrail cirrus coverage at daytime (0.64% with a standard deviation of 0.10%, in the following given as ±0.1%) and nighttime (0.66% ± 0.11%) does not differ statistically significantly, although 69% of air traffic is taking place during the day (Table 1). That is because in our parameterization contrail cirrus can persist for several hours so that contrails produced at night may still exist during daytime depending on the meteorological situation. Moreover older contrails are likely to be connected with a larger coverage since they had more time to spread. Note that we strictly distinguish between contrail cirrus being produced by nighttime flights and contrail cirrus existing at night in the following.

[14] Monthly mean global contrail cirrus RF at night amounts to 65% ± 5% of the overall global contrail cirrus RF, although coverage is equal at daytime and nighttime, i.e. the radiative effect of contrail cirrus coverage is on average about two times stronger at night than during the day. This ratio and contrail cirrus RF in general are very much dependent on the GCM's radiation scheme [*Myhre et al.*, 2009]. Whereas daytime net RF is negative for large zenith angles in many models, in ECHAM4-CCMod negative monthly mean values at daytime can only be found occasionally for high latitudes in winter months.

[15] In ECHAM4-CCMod the times of formation of contrail cirrus are not known, so that we cannot calculate the fraction of contrail cirrus RF which is caused by nighttime flights. Comparing contrail cirrus RF in an experiment where daytime air traffic is switched off without conserving the total amount of air traffic (AERO2k-night) to an experiment using the original inventory (AERO2k) we can estimate the contribution of nighttime flights to contrail cirrus RF. Note, however, that contrail cirrus coverage is not linearly dependent on air traffic. Especially in well traveled regions, ice-supersaturated areas can be covered by contrail cirrus to a large extent, so that a further increase in contrail

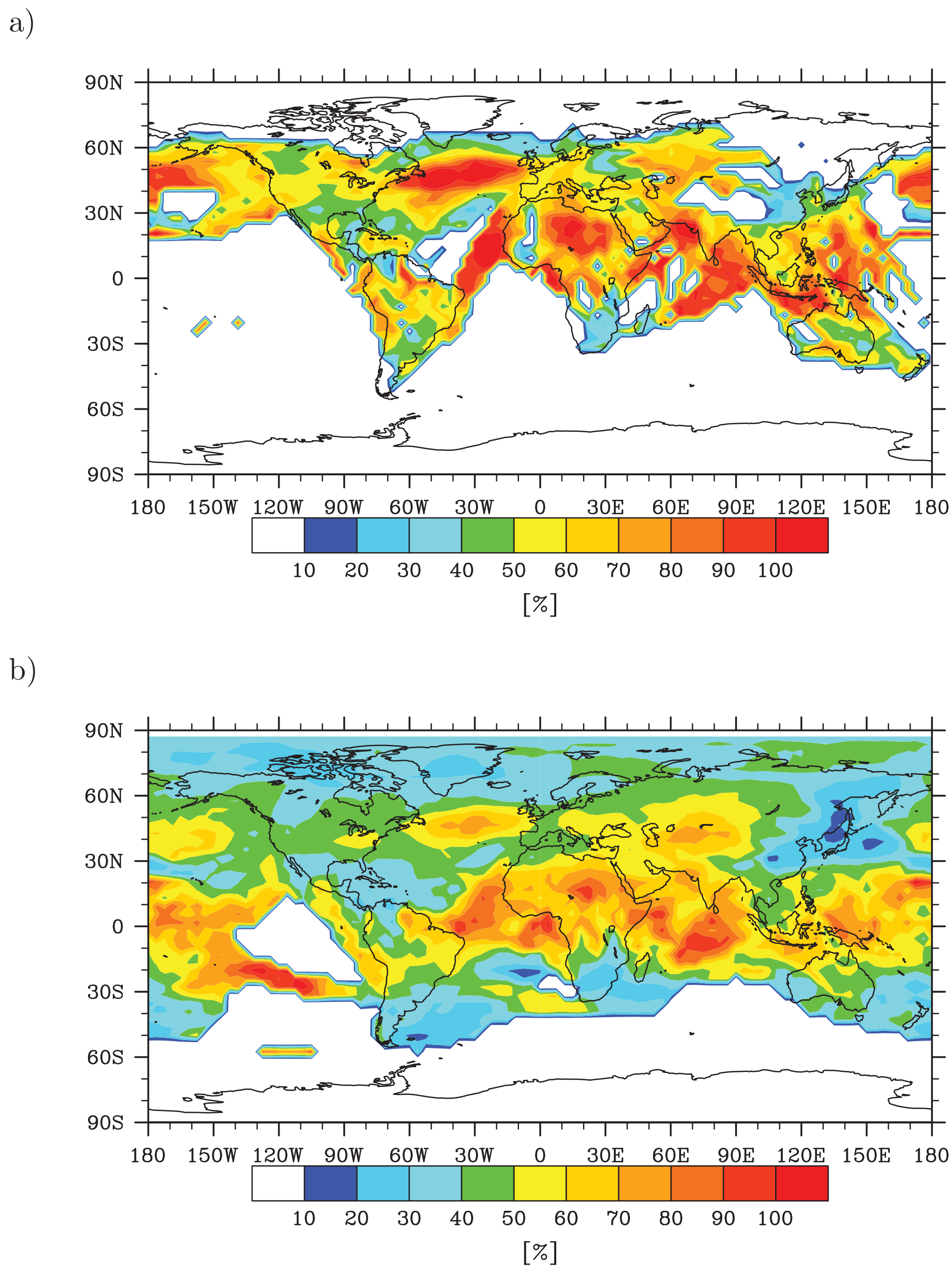

Figure 2. Annual mean contribution of nighttime flights (a) to RF of young contrail coverage and (b) to RF of contrail cirrus coverage inferred from a 10 year climate simulation of ECHAM4-CCMod. Global and regional mean contributions and their standard deviations are given in Table 1.

cirrus coverage due to contrail formation or spreading is limited. This saturation effect can lead to an overestimation of the contribution of nighttime air travel to contrail cirrus RF when estimated using the AERO2k-night experiment.

[16] The annual mean contribution of nighttime traffic to young contrail RF (Figure 2a) amounts to 64% ± 1% (Table 1) and is about double than its contribution to traffic itself, which is 31% (Figure 1b). This is due to the net RF being larger at night than during the day. In some regions with a high percentage of nighttime air travel, for instance over the North Atlantic, the percentage of nighttime travel to the overall RF even exceeds 100%. This is on the one hand caused by the net RF at daytime being negative in winter months. On the other hand it is due to the saturation effect mentioned above. The global mean contribution of nighttime flights to young contrail RF of 64% ± 1% is close to 60% as found approximately by *Stuber and Forster* [2007]. Considering the different approaches parameterizing contrails, their radiative impact and the differences in the air traffic inventory, our results are in good agreement with *Stuber and Forster* [2007], especially in the main air traffic regions USA and Western Europe (Table 1).

[17] Contrail cirrus coverage is fairly equal at night and day in the AERO2k-night experiment. Since contrail cirrus

coverage is also equal at daytime and nighttime in the AERO2k experiment, we would expect contrail cirrus caused by nighttime air traffic to have the same radiative impact as contrail cirrus caused by daytime traffic. We recall that contrail cirrus caused by nighttime flights are not the same as contrail cirrus existing at night. The pattern of the contribution of nighttime flights to contrail cirrus RF (Figure 2b) resembles, as expected, that of the percentage of nighttime air traffic to total air traffic (Figure 1b). However, especially in regions with high air traffic density, the former values are larger (Table 1). The annual and global mean contribution of nighttime flights to overall contrail cirrus RF is 49% ± 1%, despite nighttime air traffic only accounting for 31% of overall air traffic. This is likely due to the saturation effects mentioned above. To overcome this problem estimating the impact of nighttime air traffic, we will estimate the effect of shifting air traffic to daytime in section 5.

[18] Our results indicate that any estimate of the contribution of the nighttime flights to contrail cirrus RF is crucially dependent on the simulated diurnal cycle of contrail cirrus coverage. Therefore we further examine this diurnal cycle in the next section.

4. The Diurnal Cycle of Contrail Cirrus Coverage and its Dependence on Contrail Cirrus Lifetimes

[19] The daily variability of contrail cirrus coverage is determined by the diurnal cycle of air traffic density and the meteorological conditions influencing formation, spreading, advection and lifetime (as controlled by deposition, evaporation, sedimentation and precipitation) of contrails.

[20] In the main air traffic regions, Western Europe and the USA, annual mean air traffic density is largest during the day and quite small at night (Figure 3a). The diurnal cycle of young contrail coverage simulated by ECHAM4-CCMod is shifted by several hours relative to the diurnal cycle of air traffic density which is due to our definition of young contrails including all contrails with an age of up to 5 hours. The annual mean diurnal cycle of young contrail coverage in Western Europe agrees with *Marquart* [2003] who also found maximum (minimum) coverage of line-shaped contrails during the day (night). *Marquart* [2003] used the same AGCM, ECHAM4, but a diagnostic parameterization for line-shaped contrails, similar to that one of *Stuber et al.* [2006].

[21] The annual mean diurnal cycle of contrail cirrus coverage of all ages, as simulated by ECHAM4-CCMod, differs significantly from that of air traffic density and young contrail coverage (Figure 3a). It is almost constant in time without distinct maxima and minima. Contrail cirrus coverage is mainly controlled by the synoptic situation [*Burkhardt and Kärcher*, 2009]. Therefore, maxima and minima do not occur at specific times of day and average out in the annual mean diurnal cycle. This fairly flat diurnal cycle of contrail cirrus coverage over the USA and Western Europe is representative for the simulated contrail cirrus coverage in other areas as well.

[22] Contrail cirrus RF does not only depend on the increase in cloud coverage, that is induced by contrail cirrus, but also on their optical properties. The mean optical depth of contrail cirrus as calculated by the GCM is 0.017 with a standard deviation of the monthly mean values of ±0.006 in Western Europe and 0.033 ± 0.012 in North America at the main air traffic level (230 hPa) (both values are statistically significantly different from zero and from each other at the 99% confidence level) since the higher temperatures in the main air traffic areas of the USA cause a larger ice water path. Contrail cirrus coverage in Western Europe (6.3% ± 1.3%) is larger than in North America, where it reaches values of 2.8% ± 1.0% (both coverages are statistically significantly different from zero and from each other on the 99% confidence level) because the supersaturation frequency is higher and formation criteria are nearly always fulfilled in Western Europe [*Burkhardt and Kärcher*, 2011] and because of air traffic density being on average larger in Western Europe than over North America. However, no characteristic daily variability of optical depth and contrail cirrus coverage could be identified for any of these regions. Thus, our contrail cirrus longwave, shortwave and net RF resemble the diurnal cycle for a constant coverage with constant optical depth [*Meerkötter et al.*, 1999; *Dietmüller et al.*, 2008]. The net radiative effect of contrail cirrus is largest at night and smallest in the morning and in the evening (Figure 3b) and amounts on average to 223 mW/m^2 ± 54 mW/m^2 in the USA and 404 mW/m^2 ± 89 mW/m^2 in Western Europe [see also *Burkhardt and Kärcher*, 2011, Figure 3a]. Both RF values are statistically significantly different from zero and from each other at the 99% confidence level.

[23] It is difficult to judge whether the flat diurnal cycle of contrail cirrus coverage simulated by ECHAM4-CCMod is realistic. In order to understand why the diurnal cycle of contrail cirrus coverage in the ECHAM4-CCMod simulations is so smooth even though the diurnal cycle of air traffic density is very distinct, a conceptual model for contrail cirrus coverage has been developed. In the following we describe this conceptual model and the results obtained from it.

[24] For a box, representing different areas defined by latitude and longitude, this model simulates the increase of contrail cirrus coverage due to contrail spreading within a specific lifetime (t_L). The latter is in the GCM determined by the influence of microphysical processes (evaporation, sedimentation, deposition and precipitation) which are again controlled by the synoptic situation. In the conceptual model different assumptions about t_L are made (see below). Total fractional contrail cirrus coverage $B(t)$ is given by the sum of the fractional coverage of all contrails $b_{t_i}(t)$ that have formed at different time steps ($t_1, t_2,., t_n$) and the fractional coverage of the newly formed contrails $b_{new}(t)$, $t > t_n$:

$$B(t) = \sum_{i=1}^{n} b_{t_i}(t) + b_{new}(t), t > t_n. \tag{1}$$

[25] The fractional coverage of the newly formed contrails is given by $b_{new} = \frac{W_{new} \cdot L_{new}}{A}$. Contrail width is initialized, as in ECHAM4-CCMod, with W_{new} = 200 m, A is the horizontal area of the box. Only a fraction f_{new} of the flight distance AT_{AERO2k} flown in a region support the formation of persistent contrails. Contrail length associated with those newly formed contrails is $L_{new} = f_{new} \cdot AT_{AERO2k}(t)$. The fractional coverage of the newly formed contrails therefore is

$$b_{new}(t) = f_{new} \cdot AT_{AERO2k}(t) \cdot \frac{W_{new}}{A}. \tag{2}$$

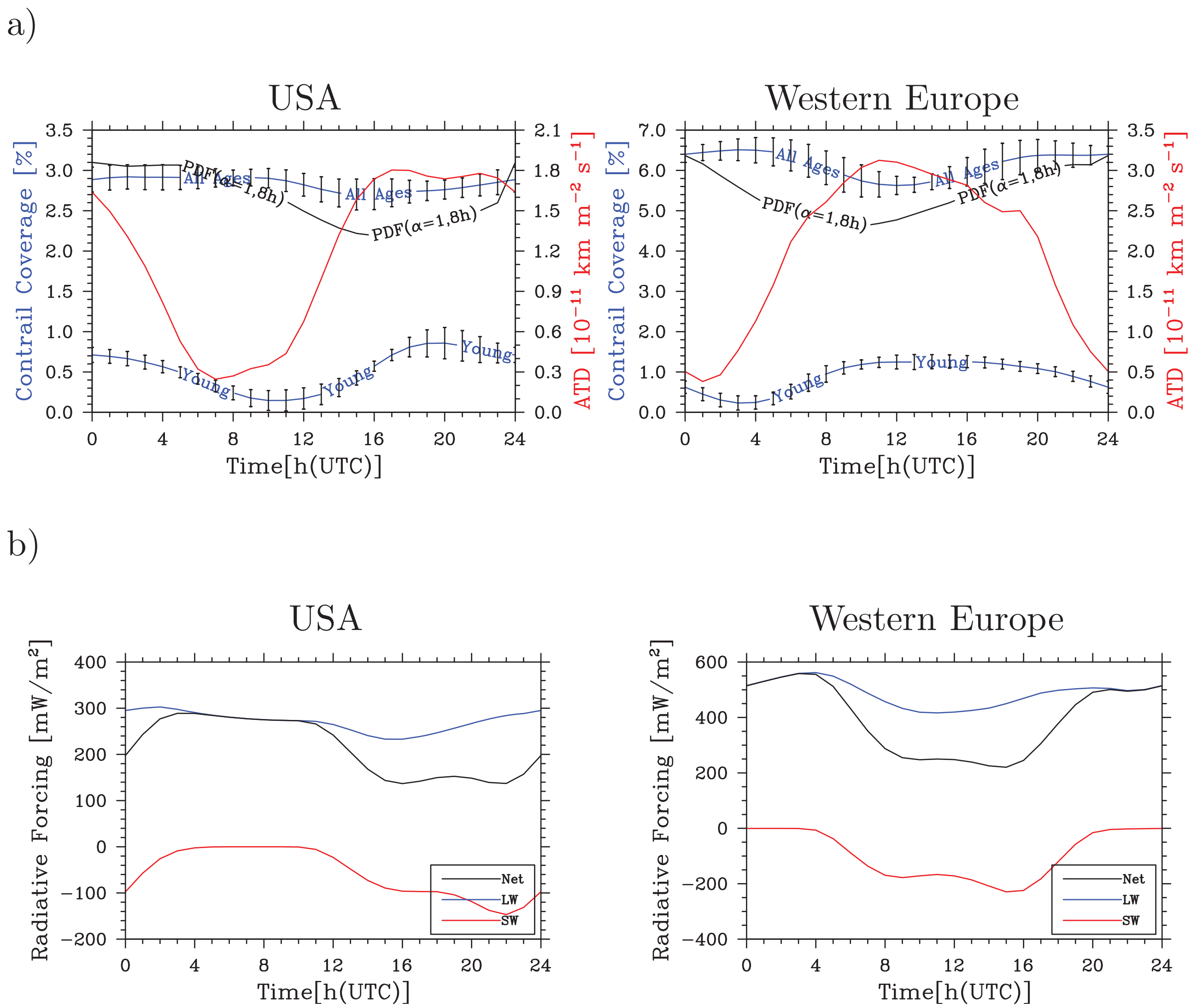

Figure 3. (a) Annual mean diurnal cycle of air traffic density (red), coverage of young contrails (blue) and contrail cirrus (blue) over the USA (130°W-65°W/55°N- 25°N) and Western Europe for UTC time (10°W- 20°E/55°N- 40°N) derived from a 5-year simulation using ECHAM4-CCMod. The black solid lines indicate contrail cirrus coverage calculated using the conceptual model assuming a Gamma-PDF for contrail cirrus lifetime with a mean lifetime of 8 hours and $\alpha = 1$ as shown in Figure 4. Error bars indicate the standard deviation at each time of day calculated from the anomaly of the monthly mean value for that time of day from its respective monthly mean. (b) Diurnal cycle of contrail cirrus longwave (LW), shortwave (SW) and net (Net) RF for the area of the USA and Western Europe derived from a 5-year simulation using ECHAM4-CCMod.

[26] In the GCM the fraction f_{new} equals the ice supersaturated and cloud and contrail free area. In the conceptual model f_{new} is set so that the daily mean coverage caused by contrails of an age of up to 5 hours in the conceptual model is equal to the respective coverage simulated by ECHAM4-CCMod .

[27] The time evolution of fractional contrail cirrus coverage $b_{t_i}(t)$ due to spreading by the vertical wind shear can be calculated as in the GCM [*Burkhardt and Kärcher*, 2009]:

$$b_{t_i}(t) = \begin{cases} b_{t_i}(t - \Delta t) + c \cdot S(t) \cdot H \cdot \dfrac{L_{t_i}}{A} \cdot \Delta t & if \quad (t - t_i) \leq t_L, \\ 0 & if \quad (t - t_i) > t_L. \end{cases} \quad (3)$$

Coverage due to a particular contrail cirrus ($b_{t_i}(t)$) initialized a time step t_i is larger than zero as long as the age of the contrail ($t - t_i$) is not larger than the predetermined lifetime (t_L). Consistent with ECHAM4-CCMod, the contrail height H is equal to the distance of the model levels in the GCM, i.e. $H \approx 700$ m in the main air traffic regions. Contrail length L_{t_i} is defined at the time of initialization as L_{new} and is not changed by spreading. The mean vertical wind shear in the upper troposphere of the box $S(t)$ is specified to be the average shear at the flight level, as simulated by ECHAM4-CCMod. It is the absolute value of the vertical wind shear vector and specifies the factor by which a contrail cover broadens per time unit. In ECHAM4-CCMod the constant c

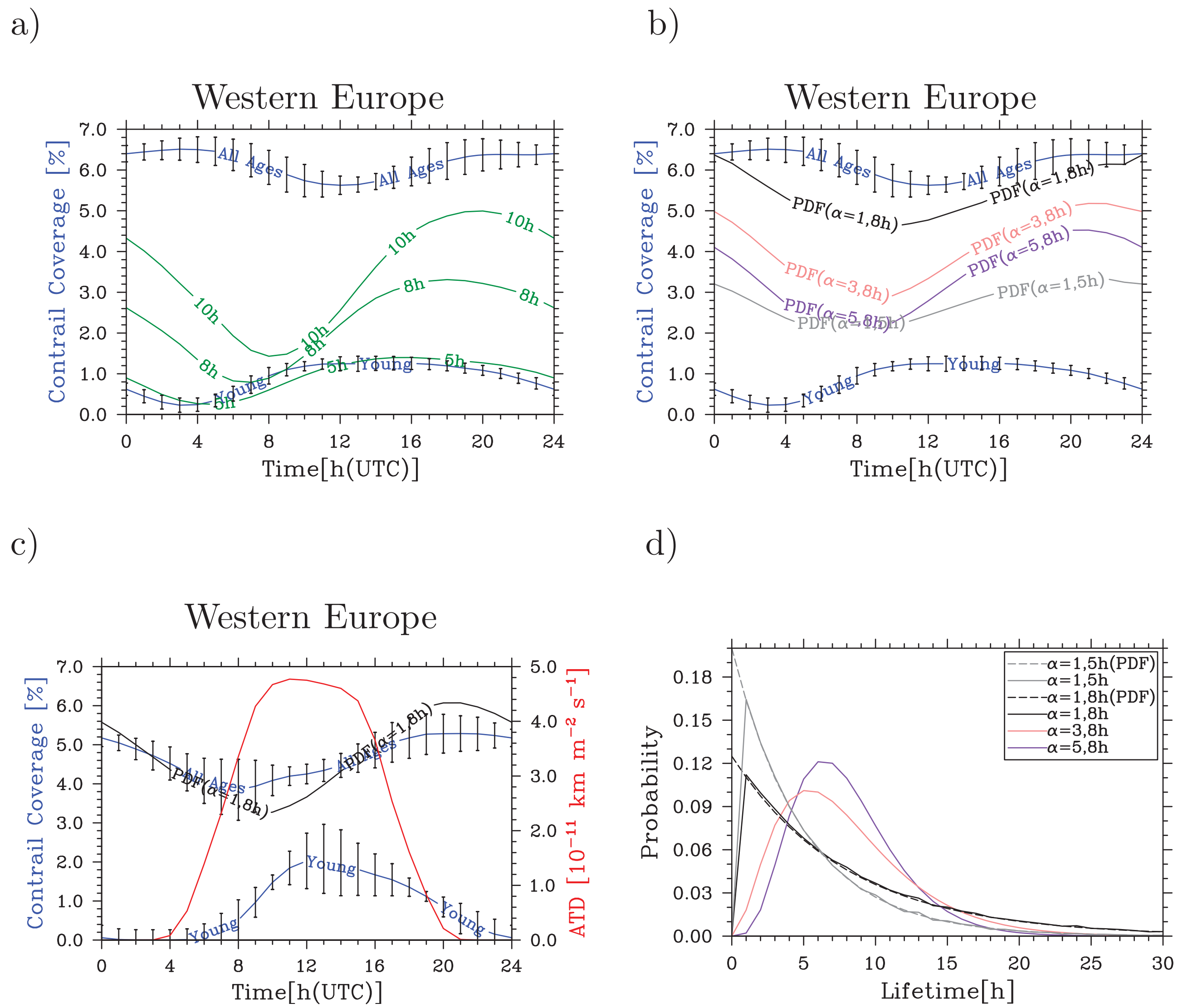

Figure 4. Mean diurnal cycle of contrail cirrus coverage derived by the conceptual model assuming (a) fixed contrail cirrus lifetimes of 5, 8 and 10 hours (green) and assuming (b) a PDF for contrail cirrus lifetimes with a fixed mean lifetime of 5 hours for α = 1(*grey*) and 8 hours for α = 1 (black), 3 (pink), 5 (purple). Blue lines as in Figure 3a. (c) As in Figures 4a, 4b, and 3a prescribing air traffic with AERO2k-id. (d) The respective Gamma-PDFs. For α = 1 the actual PDF (α = 1(PDF), dashed) and the modified PDF (α = 1, solid), where the probability for a lifetime of 0 hours is set to zero, are shown.

has been inferred from observational data to be $c = 1$, taking into account the underestimation of the vertical wind shear by a low resolution model [*Burkhardt and Kärcher*, 2009]. Maximum contrail cirrus coverage is limited by the mean ice-supersaturation frequency in the main flight levels (200 hPa-250 hPa). Applying the conceptual model, an ice-supersaturation frequency of 12% in the USA and of 15% in Western Europe has been prescribed to limit contrail cirrus coverage. We performed all the following calculations using a time step of Δt = 1 h for Western Europe and the USA. This means that our contrail lifetimes relate only to persistent contrails that exist for at least 1 hour.

[28] Applying equation (1) we first assume constant lifetimes to calculate the diurnal cycle of contrail cirrus coverage. The main effect of gradually extending the lifetime is an increase in contrail cirrus coverage (Figure 4a). The maxima and minima remain distinct and are shifted according to the assumed contrail cirrus lifetime. Assuming a constant contrail cirrus lifetime is unrealistic since many contrails can be observed to exist only a few minutes [*Vazquez-Navarro*, 2009] whereas others have lifetimes of up to 17 hours [*Minnis et al.*, 1998] or even over a day [*Bakan et al.*, 1994]. Hence, in the next step we used a probability density function (PDF) to prescribe contrail cirrus lifetime. A distribution density function that is restricted to positive values and has a long tail toward larger values (positive skewness) is the Γ-distribution, specified by the forming parameter α and the scaling parameter β, determining mean value $\alpha \cdot \beta$, maximum and variance $\alpha \cdot \beta^2$ of the distribution [*Wilks*, 1995]. For a fixed mean lifetime the variance is largest when α is small. Figure 4d shows the PDFs of contrail cirrus lifetimes with a mean of 8 hours and 5 hours and a maximum

lifetime of 30 hours. (The restriction of maximum lifetime to 30 hours in the conceptual model is not critical for the results as sensitivity studies have shown.) For decreasing α the variance increases and the most frequent lifetime moves to smaller values. The most frequent lifetime would be zero hours for $\alpha = 1$ (Figure 4d). Since contrails that disappear shortly after formation or do not form at all are already considered by the constant f_{new}, we do not allow for a lifetime of zero hours by setting its probability to zero and renormalizing the distribution.

[29] Prescribing a mean lifetime t_M, we apply the conceptual model for a variety of $\alpha - \beta$-combinations (with $\alpha = 1,.., t_M$). Drawing the contrail lifetime t_L randomly from the Γ-distribution for each newly formed contrail we calculate 10,000 diurnal cycles for each combination of α and β. These diurnal cycles were averaged for each $\alpha - \beta$-combination, to derive the respective mean diurnal cycles. This was performed for mean lifetimes t_M = 5, 6, 7, 8, 9, 10 h. When varying α or β young contrail coverage, as simulated by the conceptual model, changes. Therefore, for each $\alpha - \beta$-combination the constant f_{new} has to be reevaluated so that young contrail coverage from the conceptual model reproduces young contrail coverage from ECHAM4-CCMod. This leads to very similar diurnal cycles of young contrail coverage in the GCM and the conceptual model over Western Europe and the USA (not shown).

[30] With growing variance (decreasing α), the diurnal cycle of contrail cirrus coverage derived by the conceptual model resembles more and more that of ECHAM4-CCMod (Figure 4b). The minimum in contrail cirrus coverage is filled in and moves to later hours. We conclude that the large variance of contrail cirrus lifetime in combination with the spreading of contrails is responsible for the flattening out of the annual mean diurnal cycle of contrail cirrus coverage. Moreover, the mean contrail cirrus coverage increases with growing variance because a large variance of contrail cirrus lifetime means many short-lived contrails on the one hand, but also a growing number of contrails with a long lifetime. These few contrails spread continuously over a long time period and cover a larger area than young contrails that did not spread that much. For a mean lifetime of 8 hours (or 9 hours) and $\alpha = 1$, i.e. a variance of 64 h^2 (or 81 h^2), we get the best agreement of the contrail cirrus diurnal cycles as simulated by the conceptual model and ECHAM4-CCMod (Figures 3a and 4b). This does not necessarily represent the lifetime of contrails within ECHAM4-CCMod, as the assumption of a different shape of the PDF or keeping the vertical shear variable within the conceptual model would lead to different estimates of mean lifetime and variance. Note, that our mean lifetime relates only to those persistent contrails that have a minimum lifetime of 1 hour. In order to estimate the sensitivity of our results to the mean contrail cirrus lifetime, we use the conceptual model to simulate the coverage of persistent contrail cirrus that have an average lifetime of 5 hours and the largest variance (25 h^2 for $\alpha = 1$) (Figure 4b). The result is a lower contrail cirrus coverage with nearly the same diurnal cycle than when assuming a mean lifetime of 8 hours and the largest variance. Even though our conceptual model is very idealized, the study demonstrates that a large variance of contrail cirrus lifetimes leads to a flat diurnal cycle of contrail cirrus coverage and to an increase in mean coverage.

[31] Over Western Europe the timing of the minimum of contrail cirrus coverage at about 12 UTC could not exactly be reproduced by the conceptual model. A reason is likely that the conceptual model does not capture advection of contrail cirrus from other areas into the box. In ECHAM4-CCMod the advection of contrails from upstream areas is particularly large over Western Europe since Europe is situated downstream of the transatlantic flight corridor. Rerunning the experiment with the air traffic inventory that contains only daytime flights (AERO2k-id) reduces the advection at nighttime and leads to an even better agreement of the conceptual model and ECHAM4-CCMod (Figure 4c).

[32] It is difficult to say, whether the distribution of lifetimes in our model is realistic, since validation of contrail cirrus lifetimes with results from contrail tracking algorithms applied to satellite images is unfeasible due to the fact that only a fraction of our simulated contrail cirrus would be detectable in nature. In satellite images only contrails that have approximately conserved their line shape can be detected [*Minnis*, 2003]. Any contrails that have lost their line shape, in particular contrails associated with contrail clusters, are not recognized as contrail cirrus. The shape of contrail cirrus in ECHAM4-CCMod on the other hand is not known. Vazquez-Navarro [2009] estimate a mean contrail lifetime of 51 min, a median of 20 min and a largest lifetime of 14 hours. This means that the distribution of contrail lifetimes is strongly skewed with a long tail toward long lifetimes. It is exactly this property that leads in our study to the flattening of the mean diurnal cycle. Even if all the parameters of the PDF of lifetimes obtained from contrail observations would be available a number of problems in the detection and tracking may affect this PDF. Contrails merging with other contrails and contrails being intersected by other contrails in complicated outbreak situations, or contrails in the vicinity of, below, or right above, natural cirrus are much more complicated or may even be impossible to track or detect. Therefore, contrail cirrus in high humidity situations are underrepresented and the probability of long lifetimes of contrail cirrus is underestimated. Such contrail cirrus are instead counted as shorter lived contrails, leading to an overestimation of the probability of short lifetimes. Furthermore, contrails may become optically very thin so that they cannot be detected any longer. This would also lead to an underestimation of the lifetime of contrail cirrus. Thus only a fraction of contrail cirrus can be detected in satellite images over only a fraction of their life cycle.

5. Mitigation Experiment: A Flight Scenario Without Nighttime Flights

[33] To test the hypothesis of *Stuber et al.* [2006], who suggested that the climate impact of air traffic could be reduced by shifting air traffic to daytime, we perform an experiment using the AERO2k-id flight inventory in which nighttime flights are shifted to the day.

[34] The diurnal cycle of young contrail coverage in Western Europe is modified (Figure 4c). Contrail coverage is maximum a couple of hours after the maximum in air traffic and decreases at night, reaching zero 5 hours after air traffic ceases. Global mean coverage of young contrails is unchanged but their RF is statistically significantly (at the 99% significance level) reduced by about 6% (Table 2).

Table 2. Contrail Cirrus Coverage and RF in the AERO2k and the AERO2k-id Experiment[a]

	Coverage		Radiative Forcing	
	AERO2k	AERO2k-id	AERO2k	AERO2k-id
		Young Contrails		
Mean	0.08 ± 0.01%	0.08 ± 0.02%	**4.5 ± 0.5 mW/m²**	**4.2 ± 0.6 mW/m²**
		Contrail Cirrus		
Mean	0.66 ± 0.11%	0.65 ± 0.11%	40 ± 5 mW/m²	40 ± 5 mW/m²
Day	**0.64 ± 0.1%**	**0.60 ± 0.09%**	27 ± 6 mW/m²	25 ± 6 mW/m²
Night	0.66 ± 0.11%	0.69 ± 0.12%	**51 ± 7 mW/m²**	**54 ± 7 mW/m²**

[a]Annual, global mean young contrail and contrail cirrus coverage and RF from 15 years ECHAM4-CCMod simulation using the realistic flight inventory AERO2k and the idealized flight inventory AERO2k-id that contains only daytime flights while conserving total flight kilometers and emissions. Standard deviations are calculated from the monthly mean values. All coverages and radiative forcing values are statistically significantly different from zero at the 99% significance level. Statistically significant differences (at the 95% significance level) between the results in the AERO2k and AERO2k-id experiments are in bold.

The magnitude of change depends on the geographical location and is particularly large in regions, where air traffic occurs mainly at night in the original air traffic inventory e.g. over the North Atlantic RF due to young contrails is reduced statistically significantly (at the 95% level) by almost 25%.

[35] Annual global mean contrail cirrus coverage and RF do not change statistically significantly when shifting air traffic to the day (Table 2). Nevertheless, in Western Europe maxima and minima in the diurnal cycle are more distinct than in the AERO2k-experiment (Figure 4c). Maxima and minima occur in our simulations in the early night and in the early morning, approximately 8 hours after the respective extremes in air traffic. A similar diurnal cycle was found for other regions as well. Global mean daytime coverage is slightly but statistically significantly decreased when using the modified inventory. Nighttime coverage, on the other hand, may be marginally increased. Nighttime contrail cirrus RF is slightly but statistically significantly increased using the idealized flight inventory, whereas daytime contrail cirrus RF may be decreased.

[36] ECHAM4-CCMod indicates that shifting air traffic to daytime has a small but regionally significant impact on contrail cirrus RF (Figure 5). Statistically significant decreases in annual mean contrail cirrus RF can be found in many tropical areas, when shifting air traffic to daytime. This is due to a statistically significant reduction of daytime coverage, by up to 30% over the Maritime continent, South America, and North Africa, while nighttime coverage remains equal. This decrease in daytime contrail cirrus coverage is connected with a statistically significant decrease in contrail cirrus RF in the same areas.

[37] In Southeast Asia, maxima and minima of contrail cirrus coverage are more distinct than in the extratropics and change significantly when shifting air traffic to daytime (Figure 6a). The diurnal cycle of contrail cirrus coverage in South East Asia cannot be reproduced with the conceptual model since the diurnal cycle of young contrail coverage is influenced by a distinct diurnal cycle of ice supersaturation and the contrail formation criterion, whereas over the mid latitudes they are fairly constant. These synoptic influences are not captured by the conceptual model. Therefore, over South East Asia (as opposed to over the USA and Western Europe), the diurnal cycle of young contrail coverage as estimated by the conceptual model does not resemble that one simulated by ECHAM4-CCMod.

[38] In the northern hemisphere shifting air traffic to the daytime modifies the daily distribution of contrail cirrus coverage much more strongly in winter than in summer. In mid latitude winter short daytime hours lead to high peaks of air traffic density and consequently more distinct minima and maxima of contrail cirrus coverage. ECHAM4-CCMod suggests that the minimum contrail cirrus coverage over Western Europe occurs in winter right after the start of increase in air traffic in the morning, whereas in summertime contrail cirrus coverage is almost constant throughout the whole day (Figure 6b). This shows that restricting all the air traffic to an even shorter time window has the effect of inducing a more distinct diurnal cycle of contrail cirrus coverage. According to our model contrail cirrus coverage is minimum/maximum at sunrise/sunset when allowing only daytime air traffic. This means that theoretically contrail cirrus coverage during nighttime could be best reduced by restricting air traffic to very short time periods at the end of the night and in the very early morning. If air traffic was restricted to very short time periods contrail cirrus RF may additionally be reduced due to saturation effects.

6. Summary and Conclusions

[39] In this paper we discuss the contrail cirrus climate impact and how it might be influenced by changes in air traffic scheduling. The radiative impact of contrails and contrail cirrus depends on the solar zenith angle and thus on the time of day. At night contrail cirrus warm due to the modification in the long wave fluxes. During the day this warming is partly compensated for by cooling due to the additional change in the earth's albedo. It has been suggested that radiative forcing of air traffic could be minimized by banning nighttime flights [*Stuber et al.*, 2006]. This suggestion was based on a study of line-shaped contrail coverage assuming a fixed contrail lifetime of 2 hours. We use a recently developed process based contrail cirrus parameterization [*Burkhardt and Kärcher*, 2009, 2011] that enables the simulation of the life cycle of contrail cirrus and interpret the results using a conceptual model. We find that young contrail coverage (comparable to line-shaped contrails) strongly depends on the diurnal cycle of air traffic. Contrail cirrus, on the other hand, do not display a significant diurnal cycle in ECHAM4-CCMod.

[40] In order to interpret the results from the complex simulations with our atmospheric general circulation model,

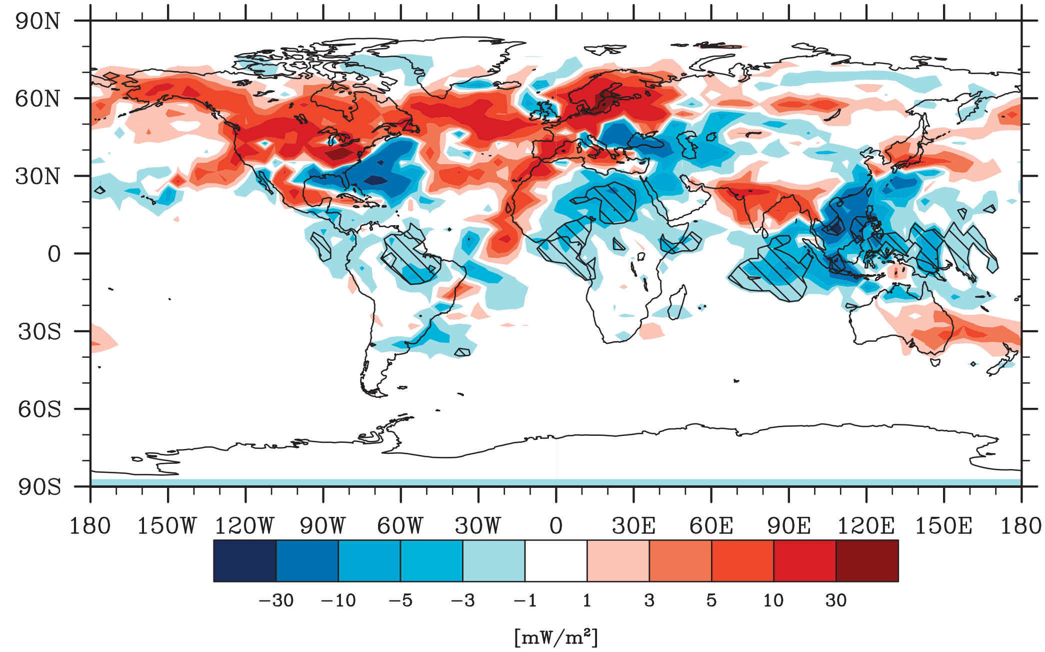

Figure 5. Difference of the annual global mean contrail cirrus RF prescribing the AERO2k-id and the unchanged AERO2k flight inventory (AERO2k-id - AERO2k). The hatched areas indicate changes that are significant at the 95% confidence interval.

ECHAM4-CCMod we develop a conceptual model to calculate the time evolution of contrail cirrus coverage. As many contrails exist a few minutes only [*Vazquez-Navarro*, 2009], but some for many hours [*Minnis et al.*, 1998; *Bakan et al.*, 1994; *Haywood et al.*, 2009], we prescribe contrail cirrus lifetimes assuming a positively skewed PDF of lifetimes within the conceptual model. With growing variance of this PDF, contrail cirrus coverage increases and the diurnal cycle flattens, resembling the diurnal cycle as simulated by ECHAM4-CCMod. Thus the high variability of contrail cirrus lifetimes, including occasionally lifetimes of a day (consistent with observations), in combination with the spreading of contrail cirrus, flattens the diurnal cycle of contrail cirrus coverage.

[41] In an idealized mitigation experiment we quantify the change in radiative forcing due to contrail cirrus when

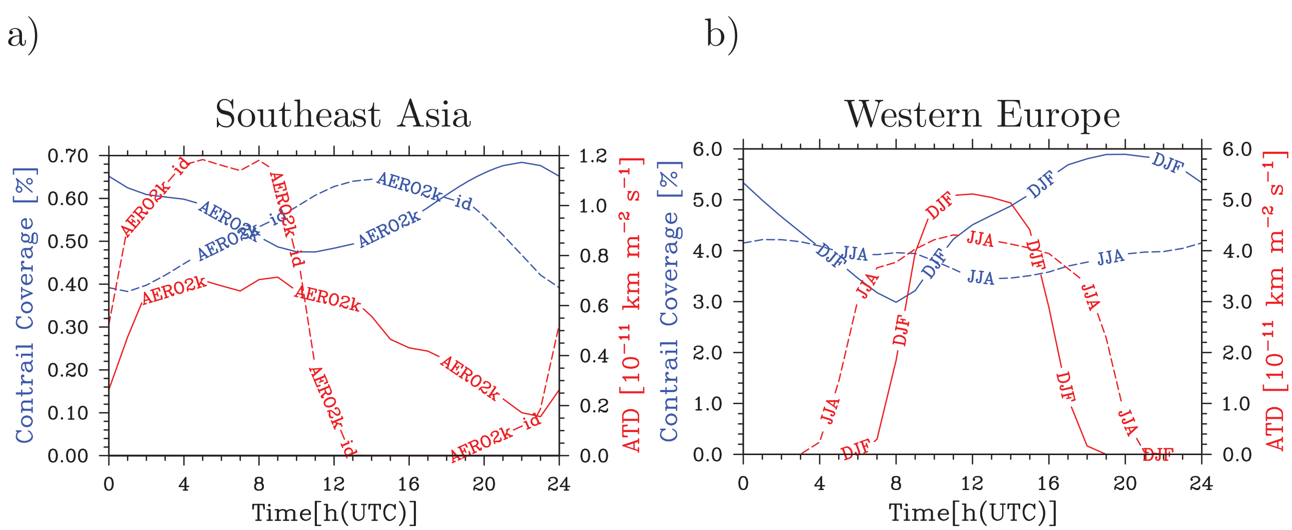

Figure 6. (a) Annual mean diurnal cycle of air traffic density (red), and contrail cirrus coverage (blue) in Southeast Asia (90°E-140°E / 20°S-20°N) derived by a 5-year climate simulation using the AERO2k and the AERO2k-id flight inventory. (b) Diurnal cycle of air traffic density (red), and contrail cirrus coverage (blue) in Western Europe (10°W-20°E / 55°N-40°N) in Winter (DJF) and summer (JJA) derived by a 5-year climate simulation using the AERO2k-id flight inventory.

shifting all the air traffic to the daytime. Our model indicates that this shift does not change annual mean nighttime coverage significantly in the main air traffic regions. In tropical regions total contrail cirrus coverage is significantly reduced when air traffic is shifted to daytime. According to our ECHAM4-CCMod, re-scheduling is therefore not a viable option for reducing the climate impact, at least not in the extratropics.

[42] Our conclusions rely on ECHAM4-CCMod simulating the life cycle of contrail cirrus coverage and properties realistically. Due to the fact that contrail cirrus cannot, or only under special circumstances, be distinguished from natural clouds there is no comprehensive data set available for validating the contrail cirrus properties simulated by ECHAM4-CCMod. From observations we know that the variance of contrail cirrus lifetimes is very large with some contrails tracked for 17 or 18 hours [*Minnis et al.*, 1998; *Haywood et al.*, 2009] or even over a day [*Bakan et al.*, 1994]. We also know that the PDF of lifetimes is positively skewed [*Vazquez-Navarro*, 2009]. We cannot rule out that our model overestimates (or underestimates) contrail cirrus lifetimes. When prescribing a mean lifetime of 5 hours combined with a large variance of lifetimes in the conceptual model, we find that the diurnal cycle of contrail cirrus coverage is still very flat. Thus our result, that a reduction of contrail cirrus radiative forcing by air traffic scheduling may not be possible, is not strongly dependent on the average lifetime of contrail cirrus simulated by ECHAM4-CCMod. Contrail cirrus lifetimes are constrained by the size of the supersaturated area in which the contrails form [*Burkhardt and Kärcher*, 2009]. As more data become available on typical horizontal and vertical dimensions of individual supersaturated areas it may become possible to estimate typical lifetimes of contrails from the dimensions of the constraining supersaturated areas.

[43] As the correct representation of the diurnal cycle of contrail cirrus is crucial for the evaluation of the impact of air traffic scheduling, more effort should be made to understand the contrail cirrus diurnal cycle. Our work indicates that the observed large variance of contrail cirrus lifetimes makes a simple shift of air traffic to daytime hours less effective or even ineffective. Thus research into other mitigation options, such as rerouting air traffic around ice supersaturated areas, changes in the altitude of air traffic, the use of alternative fuels or technological options related to jet engine and airframe development, becomes even more important.

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