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Sensitivity of contrail coverage and contrail radiative forcing to selected key parameters

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ABSTRACT

Estimates of global mean radiative forcing of line-shaped contrails are associated with a high level of uncertainty. Recent estimates for present day air traffic range from 5.4 mWm^{-2} to 25.6 mWm^{-2}. The aim of this research paper is to systematically study the sensitivity of contrail radiative forcing to selected key parameters and to highlight the most important factors for this large uncertainty range, while employing an improved version of the ECHAM climate model.

The dominating parameters on contrail radiative forcing are found to be the detection threshold used for calibrating contrail coverage to observations, and the mean optical depth. Assuming a detection threshold of 0.05 instead of 0.02 yields an increase of the total coverage, resulting in a 146% increase of global mean contrail radiative forcing. Employing a globally constant optical depth of up to 0.3, increases the net radiative forcing by 140% over the reference case which has a mean optical depth of 0.08. An upgraded parameterisation of potential contrail coverage yields a significantly larger amount of tropical contrails, increasing the contrail radiative forcing by 53%. The calibration to an alternative observation region along with the assumption of a higher visibility threshold yields an increase of the radiative forcing by 46%. Moderate sensitivity of global contrail radiative forcing (~15%) is found for an improvement of model climate and for changes in particle shape. The air traffic inventory, air traffic density parameter, and the diurnal variation of air traffic have only a small effect on global and annual mean contrail radiative forcing, but their influence on regional and seasonal contrail radiative forcing may nevertheless be important.

1. Introduction

Contrails are line-shaped ice clouds which form as a consequence of water vapour emissions and heat released from aircraft if ambient conditions at flight levels are suitable. Linear contrails can persist for many hours and may evolve into contrail cirrus clouds. Within this study, only linear contrails will be considered. These additional clouds influence the Earth's radiation budget and thereby contribute to climate change. Air traffic in total contributes only 3.5–4.9% to the total anthropogenic radiative forcing (Lee et al., 2009), whereof up to one-fifth originates from linear contrails. Nevertheless, the climate impact of air traffic is of major concern, as this sector is one of the fastest growing anthropogenic emission sectors with growth rates of about 5% per year (Airbus, 2009).

Although contrails have received special attention in aviation climate research, large uncertainties associated with the radiative impact of linear contrails and aged contrail cirrus remain. The IPCC (Penner et al., 1999) gave an uncertainty range for the radiative forcing of linear contrails of 5 mWm^{-2} to 60 mWm^{-2} for the air traffic of 1992. More recent studies determined the radiative forcing of linear contrails ranging from 2.8 mWm^{-2} (Stuber and Forster, 2007) to 12 mWm^{-2} (Rap et al., 2010) for air traffic in 2002 and from 5.4 mWm^{-2} to 25.6 mWm^{-2} for air traffic in 2005 (Lee et al., 2009). This wide range of global mean contrail radiative forcing values is associated with deviating assumptions of important key factors and different methodologies.

The aim of this study is to systematically examine the influence of various key factors on contrail coverage and radiative forcing within a global climate model. Aspects like the model climate, the parameterisation of potential contrail coverage, the contrail optical depth, the detection threshold of contrail observations, the calibration region, the air traffic inventory, the air traffic density

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parameter, the particle shape, and the diurnal variation of air traffic are investigated. The relative importance of these parameters is studied and discussed in the context of the large uncertainty range of previous contrail studies.

2. Methodology

2.1. Model description and evaluation

The parameterisation for line-shaped contrails developed by Ponater et al. (2002) has been applied in the ECHAM4.L39(DLR) climate model (E39SLT) and in an upgraded version ECHAM4.L39 (DLR)/ATTILA (E39A) (Reithmeier and Sausen, 2002; Stenke et al., 2008). The Lagrangian transport scheme in E39A can maintain steeper and more realistic gradients of highly variable tracers than the semi-Lagrangian transport scheme in E39SLT. E39A shows a significant reduction of systematic errors of temperature and humidity in the upper troposphere and lower stratosphere (UTLS) (Stenke et al., 2008). In a detailed comparison Obermaier (2007) concluded that water vapour observations are reproduced better with E39A than with E39SLT. Fig. 1 shows vertical profiles of the simulated annual mean relative humidity with respect to ice for northern mid and polar latitudes in comparison with ERA40 data. The reduction of the humidity bias entails a reduction of the temperature bias in the UTLS through radiative effects. The representation of both, temperature and humidity, is crucial for the atmospheric susceptibility to contrails according to the thermodynamic theory of contrail formation (e.g., Schumann, 1996), hence, more realistic results of contrail coverage and their properties are expected.

The potential contrail coverage, defined as the atmospheric ability to form contrails (Sausen et al., 1998), is calculated instantaneously within the climate model at each time step. The three-dimensional actual contrail coverage is calculated from the product of potential contrail coverage and air traffic density. The visible contrail coverage (optical depth $\tau > 0.02$) is randomly overlapped over all model levels and is then adjusted to regionally observed contrail coverage (Bakan et al., 1994) by means of a calibration factor. Taking into account the increase of air traffic in this region since the original observation dates, the visible contrail coverage over Europe and the North-East Atlantic region is calibrated to a value of 0.75%, similarly to Rädel and Shine (2008). Within the present study, 3-year simulations of year 2000 conditions are analysed.

The radiative effect of contrails is determined by the fractional coverage, the optical properties of contrails, the contrail temperature, and the change of the system albedo. As in previous studies, the stratosphere-adjusted radiative forcing has been calculated online using the method developed by Stuber et al. (2001). Because longwave scattering is not included in the ECHAM4 standard radiation scheme, the longwave radiative forcing of optically very thin contrails is systematically underestimated by 25%, therefore it has been corrected as suggested in Marquart and Mayer (2002), unless stated otherwise.

Recently, a benchmark test involving five different radiative transfer models was performed by Myhre et al. (2009). A homogeneously distributed "contrail coverage" of 1% with $\tau = 0.3$ was assumed globally at an altitude of 11 km in all participating models. A substantial model dependency was found in the distribution and magnitude of contrail net radiative forcing, not only because of different radiation codes, but also due to the differing background climate. The most distinct differences were found in regions where natural cloud cover is large. Global mean net radiative forcing varied by ±25% around the multi-model mean of 144 mWm^{-2} with even larger deviations in the long- and shortwave forcing components. In order to evaluate the performance of the ECHAM4 radiation scheme for contrail studies, this benchmark test has been reproduced with E39A. Fig. 2 shows the respective distribution of the annual mean contrail net radiative forcing. The largest radiative impact occurs over regions with few natural clouds, e.g. deserts and subtropical oceans, while low net contrail forcing is found along with high natural cloud cover and low surface temperatures. The results are qualitatively consistent with the distributions presented in Myhre et al. (2009). The global mean net radiative forcing for 1% homogeneous contrail coverage is 140 mWm^{-2} (210 mWm^{-2} and −70 mWm^{-2} for the uncorrected longwave and shortwave components, respectively) and thus very close to the multi-model mean given by Myhre et al. (2009). If the longwave radiative forcing contribution was corrected for the systematic underestimation, the

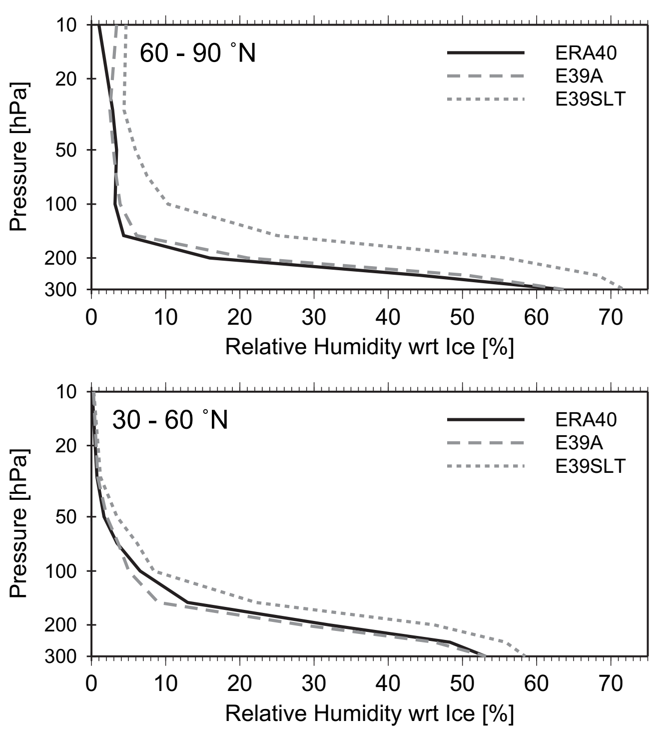

Fig. 1. Relative humidity with respect to ice for northern hemisphere polar (top) and mid latitudes (bottom) for E39A and E39SLT in comparison with ERA40 data.

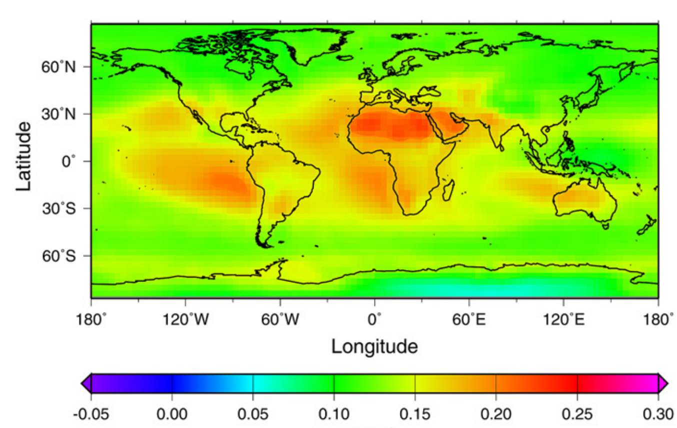

Fig. 2. Annual mean net radiative forcing [Wm^{-2}] for 1% homogeneously distributed "contrail coverage" representing a benchmark test for the ECHAM radiation scheme (Please note the slightly different colour scale compared with Myhre et al., 2009.).