Simulating Contrails with COSMO-ART Based on Real Time Flight Tracks

S. Gruber*, B. Vogel, H. Vogel
Institute of Meteorology and Climate Research, KIT, Germany

J. Bechtold, M. Jung, H. Pak
Institute of Air Transport and Airport Research, DLR, Cologne, Germany

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ABSTRACT: Condensation trails (contrails) from aircrafts are among the most obvious indications showing anthropogenic activities impacting the atmosphere. A parameterization to simulate the formation and life cycle of contrails has been implemented into the high resolution regional numerical model system COSMO-ART (Baldauf et al., 2011; Vogel et al., 2009).
Depending from the Schmidt-Appleman criterion (Schumann, 1996), that decides whether the environmental conditions are favorable for the formation of contrails, the parameterization computes additional ice water content and number concentrations. The following life cycle, consisting of processes like advection, deposition of water vapor and sublimation is described using the two moment cloud microphysical scheme of Seifert and Beheng (2006), in which the new parameterization scheme is embedded. This method allows also the treatment of so called contrail cirrus that is basically aged contrails which more and more develop into wide spread and optical thin cirrus.
A basic data set provided by the German Aerospace Center - Institute of Air Transport and Airport Research contains the spatial and temporal high resolved trajectories of a limited number of sample flights over Central Europe.
First model results are compared with satellite pictures for the simulated days. Besides the conditions for formation and the life cycle of contrails and contrail cirrus, the influence on the upper troposphere cloud coverage of these man-made clouds over Germany is examined.

1 INTRODUCTION

Besides the modification of profiles for radiative active gases like carbon dioxide and nitric oxides by direct emissions, air traffic causes changes in the microphysical and optical properties of high level clouds by contrails (Schumann, 1996) and the indirect aerosol effect (Hendricks et al., 2005). The latter two phenomena are not well understood till now, but nevertheless quite easily to observe. They occur mostly in the upper troposphere and lower stratosphere. In both areas, that are, apart from this, quite pristine, important processes influencing the radiative budget of the atmosphere take place, as they offer favorable conditions for cirrus clouds.

Contrails, contrail cirrus and contrail induced cloudiness influence the radiative budged in a way that is comparable to thin natural cirrus clouds (Sausen et al., 2005). But important properties like the optical depth or the spatial and temporal extent of occurrence is still not investigated well enough and also not quantified. It is assumed, that the influence of aged contrails and contrail induced cirrus is of a stronger importance than the one originating from young, line shaped contrails (Eleftheratos et al., 2007).

Former studies mainly used global circulation models to simulate line shaped and aged contrails e.g. (Marquart et al., 2003). The global influence can be examined, although averaging in time and area is required. In this context, a global mean of contrail coverage of 0.1 - 2 % seems to be negligible (IPCC, 2013). But still, there are estimations for situations with up to 10 % for example over Central Europe. Compared to a globally mean radiative forcing of about 6 – 15 mW m^{-2}, local impacts of more than 300 mW m^{-2} seem to be possible (Burkhardt and Kärcher, 2011).

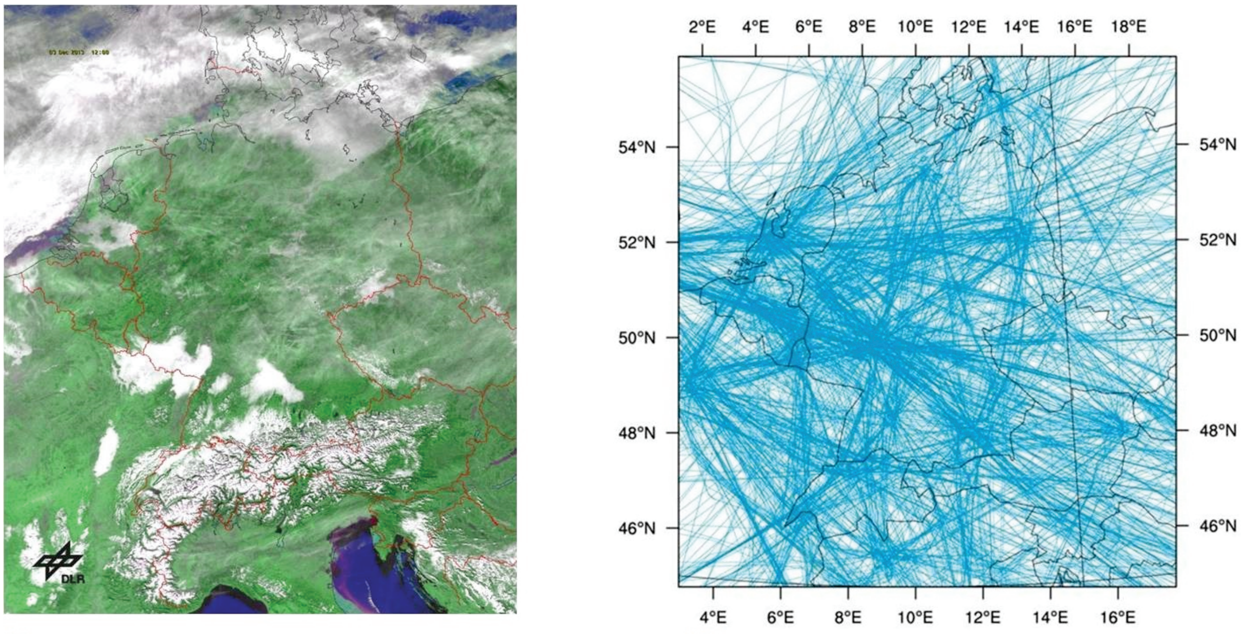
* *Corresponding author:* Simon Gruber, Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT), D-76344 Eggenstein-Leopoldshafen, Germany. Email: simon.gruber@kit.edu

Another group of projects calculates single contrails with large-eddy models (Lewellen et al., 2001; Unterstrasser, 2014). Here, the process of forming and the vortex dynamics are represented fairly exact. Parameter studies allow investigating how and under which conditions contrails are persistent and how microphysical and optical properties change during a contrail life cycle. An obvious drawback of this method is that it is not applicable on a larger spatial area.

The here presented study combines both approaches. The regional atmospheric model COSMO-ART (Baldauf et al., 2011; Vogel et al., 2009) is used, that allows besides high spatial and temporal resolution also the treatment of processes that deal with the influence of aerosols and trace gases. The model is extended by a parameterization based on recent results from large-eddy-simulations (Unterstrasser, 2014; Schumann, 2012) for taking into account the formation of contrails.

2 DATA SET

For testing the developed methods, one single day was picked because of its relatively high density of contrails combined with apart from this, mostly cloud-free conditions (Fig. 1 (a)). Despite of a thick band of clouds over the North- and Baltic Sea, lots of line shaped contrails and diffuse cirrus clouds can be seen. Especially the last mentioned consist to a large extent of contrail induced cloudiness, as shown later.



(a) (b)

FIGURE 1: (a) Satellite product for Central Europe, 3 December 2013, 12 UTC; (b) Trajectories generated from ADS-B data for the COSMO-DE domain, 3 December 2013, 08 UTC – 16 UTC.

Compared to many global modeling studies, this project uses a new kind of data set. Instead of statistical calculations for globally averaged fuel consumption (Ferrone, 2011), the basic data consists of exact flight trajectories, available over a limited area, that are recorded from real time based data (flightradar24, 2015) and provided by the Institute of Air Transport and Airport Research, DLR, Cologne, Germany. In Fig. 1 (b), all read in trajectories are depicted.

The simulation takes place on the COSMO-DE domain, with a horizontal grid size of 2.8 x 2.8 km and 80 vertical levels. As meteorological boundary data, COSMO reanalysis are used.

3 METHODS

The regional non-hydrostatic atmospheric model COSMO-ART (Consortium for Small Scale Modeling, Aerosol and Reactive Trace Gases) with a coupled scheme for the cloud microphysics that uses a two moment approach (Seifert and Beheng, 2006) serves as base to this study. For a better representation of the special characteristics of young contrails, that is at first the small particle diameters and the large number densities, their microphysical processes are treated separately from the natural cloud ice, yet still allowing the possibility for the different classes for cloud ice and contrails to interact with each other. As the contrails microphysics is embedded in the cloud scheme and thus being calculated online, a diagnostic treatment of the relevant processes is avoided.

At first, the Schmidt-Appleman-Criterion (Schumann, 1996) is checked. Depending on environmental pressure and temperature, various parameters affected by engine type and burned fuel, a critical temperature TLC can be calculated in such a way, that environmental temperatures lower than TLC force the mixing of exhaust plume and environmental air to produce supersaturation. In case of lower temperatures, the model allows the formation of a contrail for the distinct grid point at the current time step.

The developed parameterization then provides source terms for contrail ice by following in large parts the contrail prediction model CoCiP (Schumann, 2012). First, using Eq. 1, initial ice mass and numbers are generated:

$$IWC_0 = IWC_A(\dot{m}_F) + q_V - q_{SAT} \quad N_0 = IWC_0 / m_0 \tag{1}$$

Here the entire amount of water vapor causing local supersaturation ($q_V - q_{SAT}$) is converted into contrail ice. An additional source IWC_A considers the impact of the flying aircraft itself. As the engine burns a certain amount of fuel, additional water vapor is set free, quantitatively depending mainly from the fuel flow $\dot{m}_F$. Hence, this term may vary for different engines. The initial number of ice crystals is calculated by assuming a constant diameter (d_0 = 1 μm) for the very young particles.

Afterwards, the crystal loss in the wake of the aircraft is taken into account by Eq. 2. Owing to adiabatically warming (ΔT_{AD}) by a sinking movement in the downstream vortex, a certain part of particles (ΔIWC_V) sublimates. The strength of this downwash process depends from vertical velocity (w) and stratification (NBV). Dilution caused by extension of the contrail diameter also reduces the concentration, where also a slight growing of the particles is assumed (Eq. 3).

$$IWC_C = IWC_0 - \Delta IWC_V(\Delta T_{AD}, w, N_{BV}) \tag{2}$$

$$N_C = n_0 f^{1.1}; f = IWC_C / IWC_0 \tag{3}$$

4 RESULTS

The computed ice water path (IWP) for the simulated day at 12 UTC is compared in Fig. 2. In Fig. 2 (a), the IWP of the reference run, that is, without the new contrail parameterization, is displayed. Fig. 2 (b) shows the entire IWP for a simulation with the parameterization switched on. Here, natural IWP as well as additional contributions from contrails, contrail cirrus and contrail induced cloudiness in general is included. Parts of the visible but rather blurred cirrus cloud coverage over Germany and Eastern Europe in Fig 1 (a) is strongly intensified when applying the parameterization. Also, certain patterns like the cirrus over the center of Germany and the high-level cloudiness located south of the Alps seem to be caused by contrails and the resulting contrail cirrus.

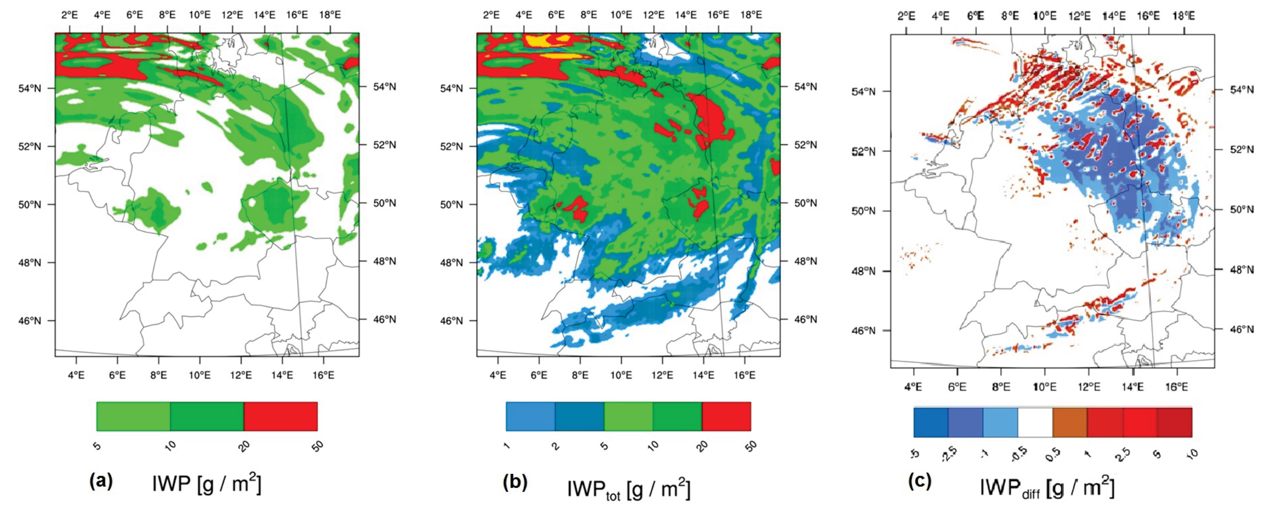


FIGURE 2: 3 December 2013, 12 UTC: Ice water path from the reference simulation (a), for a simulation with contrails (b) and difference in natural ice water path for simulation with and without contrails (c).

The contrail microphysics is treated separately from the one for the natural ice phase, but nonetheless, feedbacks are possible. For example, both hydrometeor classes can compete for the available water vapor. The difference in natural IWP at 12 UTC for two simulations is displayed in Fig. 2. (c) The values from the reference run are subtracted from the results of the simulation with the parameterization switched on. Natural IWP means here, also contrail ice exceeding a certain threshold mass is taken into account, as those crystals are of a circus-like size and occur in a similar number density. Shown here is therefore the quantitative influence of contrails on natural cirrus clouds. The line-shaped structures, depicted in red, consist of additional ice particles that originally occurred in contrails but grew in such an extent, that their mass is comparable to natural crystals. Negative values in blue indicate a reduction in natural cloudiness because of existing contrails. As contrails and contrail cirrus contain water vapor, that now cannot neither be transported nor serve to form cirrus. Compared to the IWP of the reference run in Fig. 2 (a), the additional contrail cirrus reaches IWP up to 10 g m^{-2} and is of a thickness equal to thin natural cirrus.

Concerning their microphysical properties, contrails differ strongly from natural clouds. For the simulated contrail ice in the layer of 10.000 m height at 10 UTC, Fig. 2 shows in (a) the ice water content (IWC), in (b) the particle number density (N) and in (c) the volume radius (r_V). The maximum contrail age here is two hours. At this time, they still consist of lots of very small ice crystals. The number density lays on average above 100 cm^{-3}, whereas the calculated particle radii, with values varying between 1 and 5 µm are about one order of magnitude underneath what is observed in natural cirrus.

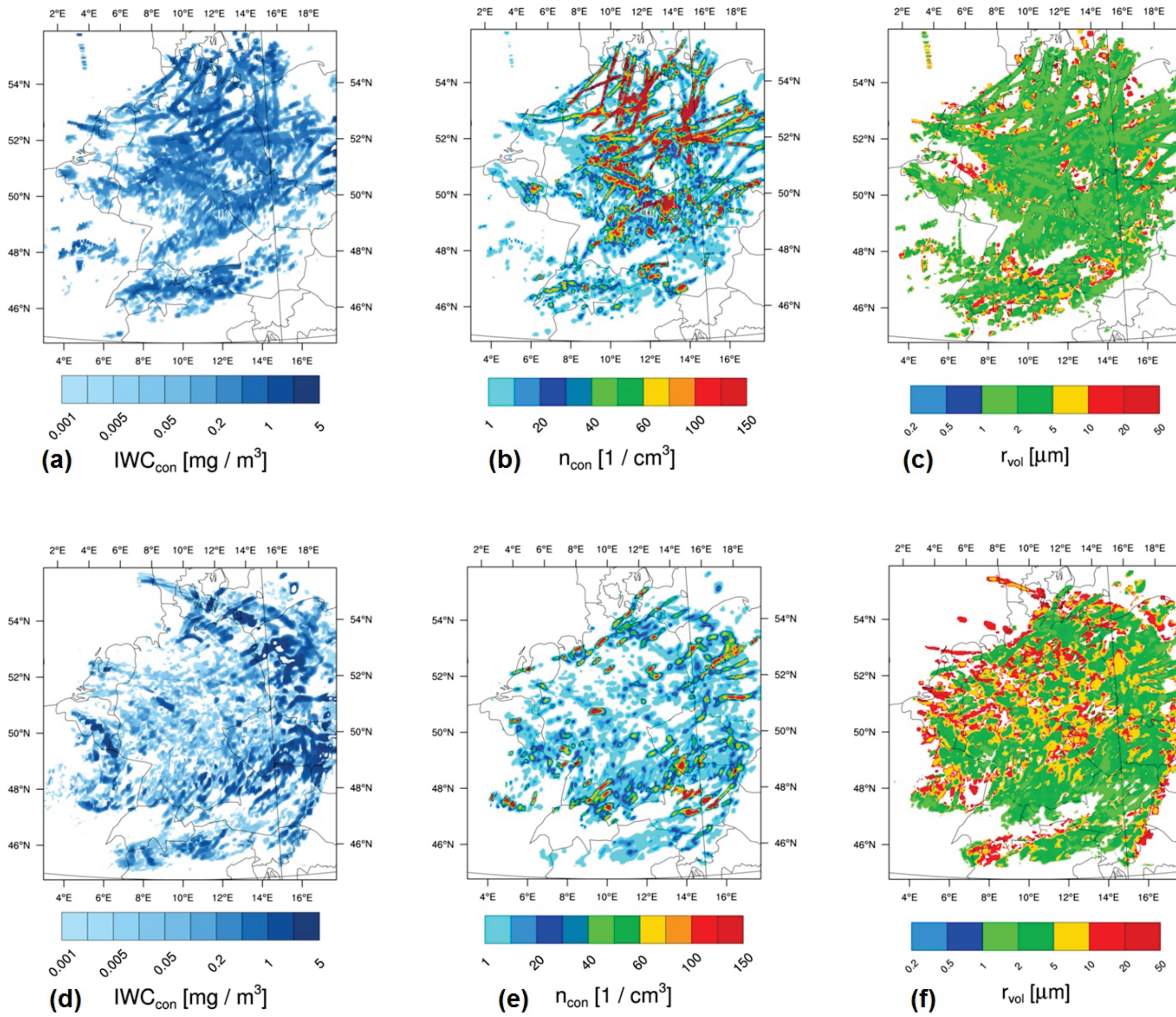


FIGURE 3: 3 December 2013: Properties of young and aged contrails, top row: 10 UTC, 10 300 m, bottom row: 13 UTC, 9 500 m; left: ice water content, center: particle number concentration, right: volume radius.

In Fig. 1 (c) to (d), the same variables like (a) to (c) are depicted, but now with values for three hours later. Therefore, some contrails are up to five hours old and find themselves in a phase of transition to contrail cirrus. Comparing (a) and (d), only small changes in the ice water content are observed. Obviously, because of the persistent supersaturation with respect to ice over large areas, no significant loss of mass happens. In contrast, the number density decreases strong in (e). As a consequence, the mean particle radii grow about one order of magnitude in (f) compared to (c). This is to be explained with various microphysical processes like diffusional and depositional growth.

5 CONCLUSIONS AND OUTLOOK

Modeling contrails for short time spans on the regional scale brings advantages. Using flight trajectories based on real time is prerequisite for validation. Furthermore, the online coupled microphysics allows examining feedback mechanisms between cloudiness of natural and anthropogenic origin. It was shown, that the model configuration is able to simulate the local occurrence of contrails as well as their life cycle and their influence on natural cirrus clouds.
Partly, the existence of the cirrus-like clouds observed in satellite pictures can only be explained by considering aviation induced cloudiness. A significant change in high level cloud coverage, both positive and negative occurs when taking contrails and contrail cirrus into account.
The presented study is a framework to do some first tests on the developed parameterization. In a further step, the radiative impact of contrails and contrail cirrus is to be investigated. Because of the high spatial and temporal resolution, this project can serve as a base to improve the predictability of the solar radiation budget modified by contrails and contrail cirrus. This gains a certain importance when it comes to estimate the amount of produced energy from photovoltaic systems.

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