Detection of young contrails – selected results from the CONCERT (CONtrail and Cirrus ExpeRimenT) campaign

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ABSTRACT: Large uncertainties remain in estimating the climate impact from contrails. In particular it is unknown, whether the aircraft type has an influence on contrail properties. Therefore, microphysical and radiative properties of contrails were detected with the DLR research aircraft Falcon during the CONCERT campaign in October/ November 2008. During 12 mission flights over Western Europe 22 contrails from 11 different aircraft were probed and the ice particle number density, size, extinction, contrail dimension as well as trace gas fields were measured. Here we focus on the 14 minutes sampling of the contrail of an A319. The 1 to 3 min old contrail was detected in the vortex regime. It was observed at an altitude of 10.6km and a temperature of 216K in ice subsaturated air (82%<RHI<98%). Particle concentration, extinction, and ice water content decrease within the sampling period due to contrail ageing and dilution. A vertical contrail depth of 122m has been estimated from the measurements and agrees with vortex descent simulations. Micro- and macro-physical contrail observations allow for the quantification of the contrail optical depth, playing a crucial role for the estimate of contrail radiative forcing.

1 INTRODUCTION

Contrails are produced through mixing of the hot and humid aircraft exhaust with the cold ambient air when saturation with respect to liquid water is reached. Ice may nucleate in the aerosol below the contrail formation threshold temperature (Schumann, 1996), whereby liquid plume particles compete with the exhaust soot for the formation of contrail ice crystals. If the ambient air is ice-supersaturated, the initially line shaped contrail will develop into a persistent contrail cirrus deck. Atmospheric and plume specific processes acting on different scales result in a variability of contrail properties that can be quantified using probability distribution functions (Kärcher et al., 2009). Lee at al., (2009) present a first attempt to include such a variability of contrail properties in global climate simulations. Including aircraft induced cloudiness, they derive a net median aviation radiative forcing in 2005 of 4.9% (2–14%, 90% likelihood range) of the total anthropogenic radiative forcing. Thereby, the key parameter in determining the climate impact from contrails is the contrail optical depth.

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The contrail optical depth τ can be calculated from the effective ice crystal radii, the number density, the ice water content (IWC) and the contrail depth. Still, in situ and remote sensing data on these micro- and macro-physical contrail properties in the vortex regime are sparse. Reasons for the lack of contrail data are that the detection of numerous small aerosol and ice particles with different refractive indices poses a challenge for accurate in situ measurements. Further, the resolution of satellite instruments often inhibits the observation of young contrails with ages of few minutes from space.

Few studies investigate microphysical properties of young contrails. Mean ice crystal effective radii derived from in situ data show values of 0.5 to 1µm initially (Heymsfield et al., 1998), increasing due to condensation to values of up to 5µm at 30min contrail age (Schröder et al., 2000). Mean ice crystal concentrations larger than $1000cm^{-3}$ have been detected in 5 and 8s old contrails decreasing by dilution to concentrations of a few $100cm^{-3}$ (Schröder et al., 2000) or less than $100cm^{-3}$ (Febvre et al., 2009) over the first 3min of age. The ice water content in a range of 1 to 6mg m^{-3} in young contrails has occasionally been probed at temperatures near 218K (Schröder et al., 2000; Febvre et al., 2009). Arbitrary sampling of contrails in thin cirrus clouds at temperatures near 217K leads to IWC values of 1 to 3mg m^{-3} (Schäuble et al., 2009). Another study reports values of up to 18mg m^{-3} at 236K (Gayet et al., 1996). Contrail widths of 1 to 3km have been derived for less than 30min old contrails from Lidar measurements above Germany (Freudenthaler et al., 1995).

Given the sparsity of in situ measurements of contrail microphysical properties, here we report on a new set of contrail observations. The measurements were performed in November 2008 with the DLR research aircraft Falcon. During the CONCERT campaign (CONtrail and Cirrus ExpeRimenT) numerous contrails were sampled in ice sub- and supersaturated air (50<RHI<130%). In total 22 contrails from 11 different commercial airliners were probed, including an A380, several A340 and B737 and a number of smaller aircraft such as an A319. As the data evaluation is still ongoing, we focus here exemplarily on a 14 minutes sampling event of the contrail of an A319 above Northern Germany, which is suitable for statistical data analysis. We derive particle concentrations, ice water content, and contrail depth from our data and compare them to results from vortex descent simulations.

2 FALCON INSTRUMENTATION

Figure 1. Deployment of the DLR research aircraft Falcon during the CONCERT – campaign (CONtail and Cirrus ExpeRimenT) in October/November 2008.

During the CONCERT campaign a set of particle and trace gas instruments was deployed on the DLR research aircraft Falcon. The particle size distribution of large particles (20µm - 1mm) was detected with a 2DC probe, the particle shape (2.3µm pixel size) with a cloud particle imager (CPI) and the scattering phase function of cloud particles (3µm - ~1mm) using a polar nephelometer (Gayet et al., 2006, Febvre et al., 2009). A forward scattering spectrometer (FSSP 300) probe detected the particle number density and size distribution of small particles in the size range 0.3 to 20 µm diameter (Petzold et al., 1997). The particle size distribution was evaluated assuming spherical particles and a refractive index of 1.33 for ice. During the first phase of the CONCERT campaign, an aerosol mass spectrometer (Schneider et al., 2006) was integrated in the Falcon instead of the FSSP.

The trace gas instrumentation consisted of a Lyman-α fluorescence Fast In situ Stratospheric Hgrometer FISH (Schiller et al., 2008) with a backward-facing inlet sampling water vapour with an uncertainty of 8%. In addition, nitric oxide and the sum of reactive nitrogen species NO_y were measured with a chemiluminescence instrument (Schlager et al, 1997) with an uncertainty of 8%. A chemical ionization ion trap mass spectrometer was operated to detect sulfur dioxide (SO_2) and nitrous acid HONO with an uncertainty of 30%. Contrails from different source aircraft were frequently probed with this instrumentation during the CONCERT campaign. Below we investigate data from a flight on 19 November 2008, where microphysical and chemical properties of the contrail of an A319 were measured for 14 minutes.

3 DETECTION OF CONTRAILS

Contrails were mainly probed above optically visible cirrus clouds, as this sampling strategy was found to be very effective. Predictions for high clouds or of the IWC from ECMWF analyses were used to send the aircraft into a cirrus region and the flight altitude was then adjusted based on contrail observations of the pilots. The contrail formation altitude was communicated to German Air Traffic Control, and commercial airliners flying in that region were asked to change their flight altitude to contrail formation altitudes. Then the Falcon was directed behind the airliners and contrails were detected at 5 to 85 nautical miles distance corresponding to contrail ages of 55 to 600s.

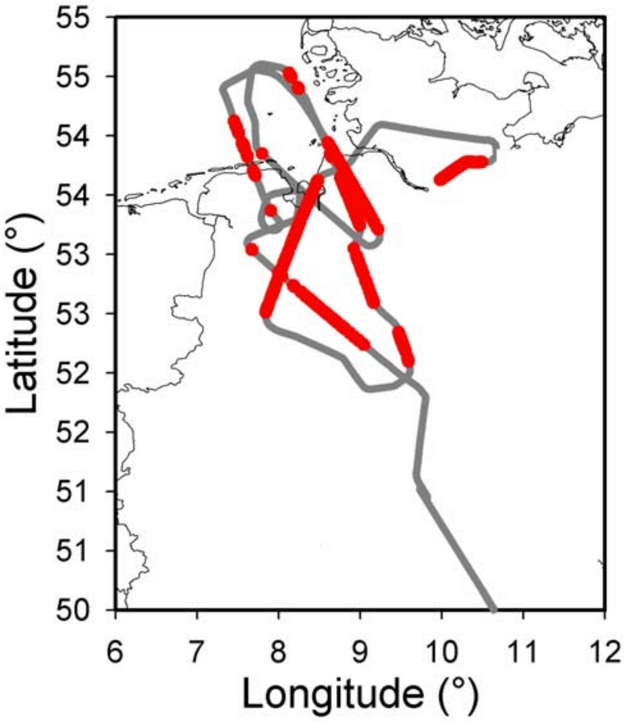

Figure 2, left panel. Flight path of the Falcon on 19 November 2009 (gray). Contrails are marked in red.

Figure 2, right panel. Photo of the contrail of the A319 which was probed by the instruments on the Falcon. The primary and the secondary wake, other contrails, and the nose boom of the Falcon can be seen.

On 19 November 2008 the Falcon five times probed the contrail of an A319, which was operating on that day exclusively as a contrail producing source aircraft. The Falcon took off in Oberpfaffenhofen, performed measurements within contrails above Northern Germany at altitudes between

10.1 and 10.8km and landed in Hamburg. The Falcon flight track, 5 contrail encounters of the A319 and contrail samplings of other aircraft are shown in Figure 2. Some contrail segments formed above cirrus clouds as seen on the photo in the right panel of Figure 2. Note that the primary and secondary wakes of the A319, contrails from other aircraft, and the nose boom of the Falcon are shown.

Measurements during the longest contrail penetration of 14 minutes from 53°N, 8°W to 54°N, 9°W are presented in Figure 3. Simultaneous peaks in the concentrations of reactive nitrogen, sulphur dioxide and particle number density are indications for a contrail encounter.

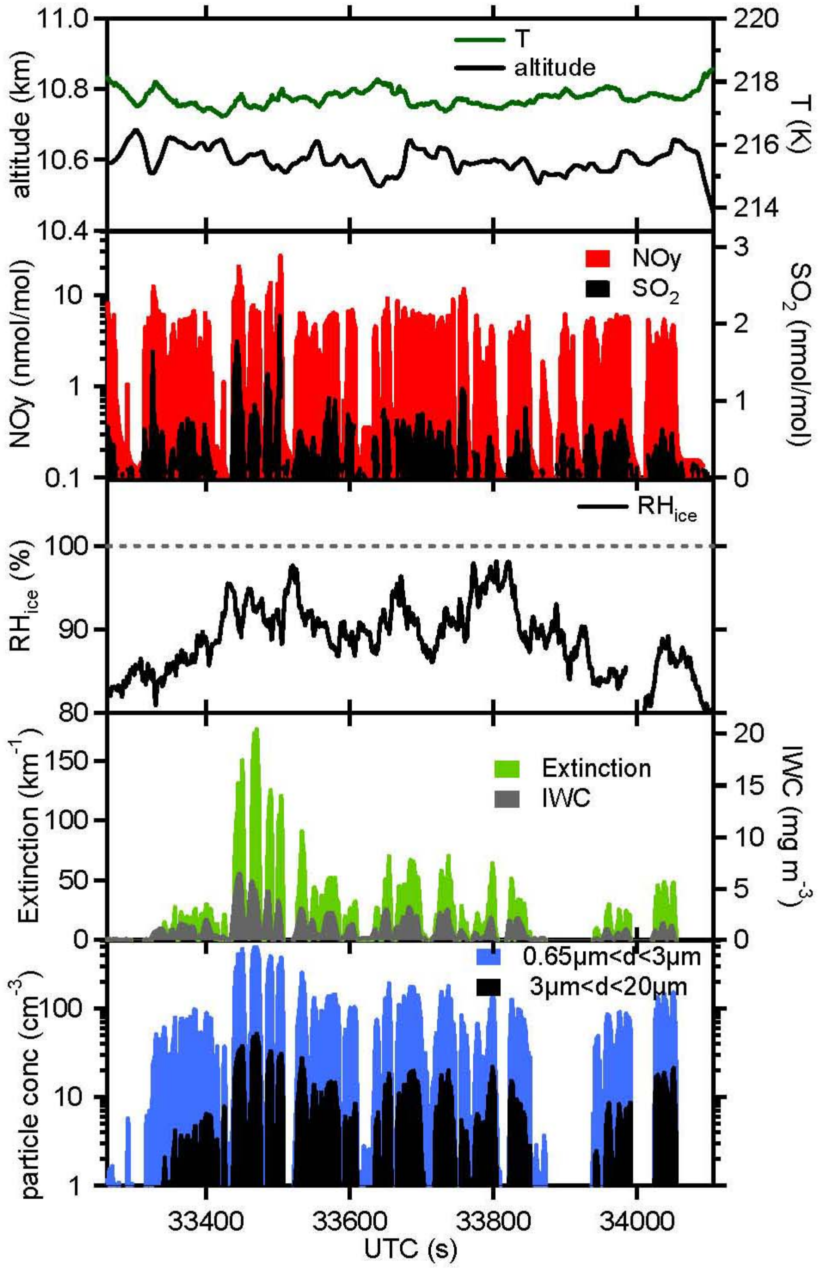

Figure 3. Sequence of 14 minutes of measurements in the contrail of an A319 performed on 19 November 2008 above Northern Germany. Temperature, altitude, trace gas mixing ratios of NO_y, SO_2 and RHI are shown in the upper three panels. The lower panels show contrail particle properties, i.e. the ice water content, the extinction of particles >3µm, and the particle concentrations in the cloud mode (3µm<d<20µm) and the haze mode (0.65µm<d<3µm). The contrail age increases from 77 to 184 s within the sampling sequence.

The contrail sequence was measured at an altitude of 10.6km and a temperature of 217.6K. Up to 27nmol/mol NO_y were observed in the contrail with average NO_y concentrations of 6nmol/mol. Such concentrations have been detected previously in the primary and secondary wake of aircraft (Schlager et al., 1997). SO_2 mixing ratios up to 2nmol/mol were measured with an average of

290pmol/mol and background concentrations of about 80pmol/mol. The air was slightly sub-saturated with respect to ice (98>RHI>82%), suggesting that the contrail was evaporating.
Total ambient particle concentrations of up to 546cm^{-3} for particles in the size range 0.65<d<20µm have been detected by the FSSP. The particle concentration shows a substantial variability within the contrail and decreases within the measurement period due to dilution of the aging contrail. Particles >3µm exhibit an extinction up to 170km^{-1} decreasing with contrail age. The ice water content in the range of 7 to 1mg m^{-3} has been derived from a combination of FSSP and CIP data.
We calculated the age of the contrail from the positions of the Falcon and the A319 and meteorological parameters by matching the advected contrail with the Falcon flight path. The contrail was 77s old at the beginning of the sampling and 184s at the sampling end. Contrail dynamics for contrail with ages of 1 to 3min is described by the vortex regime.
Besides microphysical contrail properties such as particle number density, size and ice water content, we also evaluate contrail profiles and estimate the vertical contrail depth from our measurements. The data will allow us to derive the contrail optical depth.

4 CONTRAIL PROFILE

Engine emissions are captured by the wake vortices forming behind the aircraft. Due to momentum conservation, the primary vortices descent within the first 1 to 3min transporting a large fraction of the emissions including particles downwards. The air is adiabatically heated during its downward transport, which can result in a (partial) evaporation of ice particles in subsaturated conditions with respect to ice. A small fraction of the emissions including particles remains near its emission altitude in the secondary wake. Depending on ambient saturation ratios and descent depths, the primary and/or the secondary wake might survive the vortex phase and evolve into a persistent contrail. A profile taken in the A319 contrail near 33420s UT (101s contrail age) is shown in Figure 4.

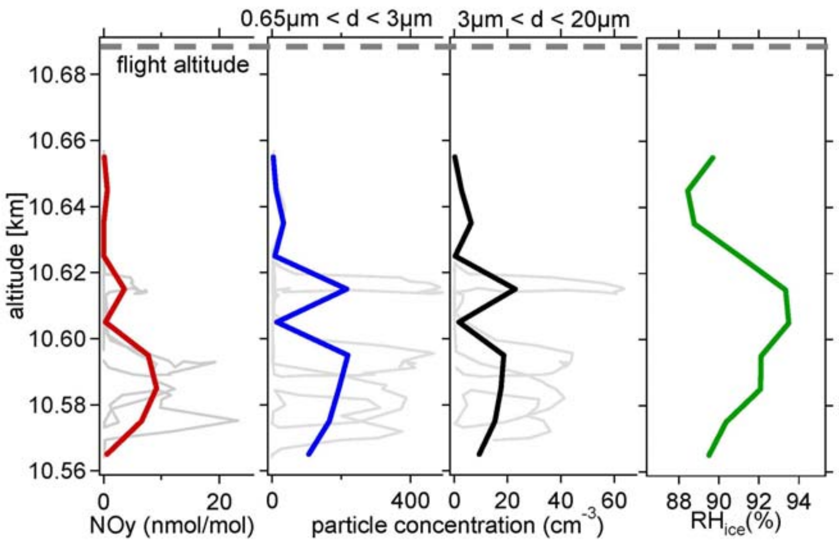

Figure 4. Profile of the NO_y mixing ratios, particle concentrations of the haze mode (0.65µm<d<3µm), the cloud mode (3µm<d<20µm), and RHI in the contrail of an A319 measured on 19 November 2008 at 33420 s UT. Thick lines are averages of the individual measurements (gray lines) in 10 m altitude intervals.

From the contrail profile, we estimate a vertical contrail depth of 122m, which is in agreement with simulations of the wake vortex descent of an A319 of 124m using the P2P model under standard ambient conditions (Holzäpfel et al., 2003).

5 CONCLUSIONS AND OUTLOOK

The CONCERT campaign provides an extensive and detailed data set on microphysical and optical contrail properties from 11 different aircraft, amongst them an A380, four A340, several B737, A319 and smaller aircraft. The data have been used for model validation (Schumann, 2009) The measurements of particle number density, size and contrail dimensions of the A319 will be used to derive contrail optical depths. Long sampling times in the contrail will allow for a statistical data analysis. The next step is to compare the contrail optical depths of the A319 to contrail samplings from other aircraft with the aim to investigate the the impact of aircraft type on contrail properties. The results including a statistical data analysis will appear soon in a refereed journal.

REFERENCES

Febvre, G., J.-F. Gayet, A. Minikin, H. Schlager, V. Shcherbakov, O. Jourdan, R. Busen, M. Fiebig, B. Kärcher, and U. Schumann, 2009: On optical and microphysical characteristics of contrails and cirrus, *J. Geophys. Res.,* 114, D02204, doi:10.1029/2008JD010184.

Freudenthaler, V., F. Homburg, and H. Jäger, 1995: Contrail observations by ground-based scanning Lidar: Cross-sectional growth, *Geophys. Res. Lett.,* 22, 3501–3504.

Gayet J.-F., V. Shcherbakov, H. Mannstein, A. Minikin, U. Schumann, J. Ström, A. Petzold, J. Ovarlez and F. Immler, 2006: Microphysical and optical properties of midlatitudes cirrus clouds observed in the southern hemisphere during INCA, *Q. J. R. Meteorol. Soc.***,**132, 1-30.

Heymsfield, A. J., R.P. Lawson, and G.W. Sachse, 1998: Growth of ice crystals in a precipitating contrail, *Geophys. Res. Lett.,* 25, 1335–1338, 1998.

Holzäpfel F., 2003: A Probabilistic Two-Phase Wake Vortex Decay and Transport Model, *Journal of Aircraft,* 40, 2, 323-331.

Kärcher, B., U. Burkhardt, S. Unterstrasser, and P. Minnis, 2009: Factors controlling contrail cirrus optical depth, *Atmos. Chem. Phys., 9, 6229-6254*.

Lee, D., D. W. Fahey, P. M. Forster, P. J. Newton, R. C.N. Wit, L. L. Lim, B. Owen and R. Sausen, 2009: Aviation and global climate change in the 21st century, *Atmos. Environ.,* 43, 3520–3537.

Petzold, A., et al., 1997: Near-field measurements on contrail properties from fuels with different sulfur content, *J. Geophys. Res.*, 102, 29867–29881.

Schäuble, D., C. Voigt, B. Kärcher, P. Stock, H. Schlager, M. Krämer, C. Schiller, R. Bauer, N. Spelten, M. de Reus, M. Szakall, S. Borrmann,U. Weers, and T. Peter, 2009: Airborne measurements of the nitric acid partitioning in persistent contrails, *Atmos. Chem. Phys. Discuss., 9*, 14165–14187.

Schlager, H., P. Konopka, P. Schulte, U. Schumann, H. Ziereis, F. Arnold, M. Klemm, D. Hagen, P. Whitefield, J. Ovarlez, 1997: In situ observations of air traffic emission signatures in the North Atlantic flight corridor, *J. Geophys. Res.,* 102, 10739-10750.

Schiller, C., M. Krämer, A. Afchine, N. Spelten, and N. Sitnikov, 2008: Ice water content of Arctic, midlatitude, and tropical cirrus, *J. Geophys. Res.,* 113, D24208, doi:10.1029/2008JD010342.

Schneider, J., S. Hings, N. Hock, S. Weimer, S. Borrmann, M. Fiebig, A. Petzold, R. Busen, B. Kärcher, Aircraft-based operation of an aerosol mass spectrometer: Measurements of tropospheric aerosol composition, *J. Aerosol Sci.,* 37, 839-857, doi: 10.1016/ j.aerosci.2005.07.002, 2006.

Schröder, F., B. Kärcher, C. Duroure, J. Ström, A. Petzold, J.-F. Gayet, B. Strauss, P. Wendling, and S. Borrmann, 2002: On the transition of contrails into cirrus clouds, *J. Atmos. Sci.,* 57, 464–480.

Schumann, U., 1996: On conditions for contrail formation from aircraft exhausts, *Meteorol. Z.,*5, 4 –23.

Schumann, U., 2009: A Contrail Cirrus Prediction Tool*, Intern. Conf. on Transport, Atmosphere and Climate*, Aaachen and Maastricht, EUR, in press.