



**Aircraft type
influence on contrail
properties**

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Abstract

The investigation of the impact of aircraft parameters on contrail properties helps to better understand the climate impact from aviation. Yet, in observations, it is a challenge to separate aircraft and meteorological influences on contrail formation. During the CONCERT campaign in November 2008, contrails from 3 Airbus passenger aircraft of type A319-111, A340-311 and A380-841 were probed at cruise under similar meteorological conditions with in-situ instruments on board the DLR research aircraft Falcon. Within the 2 min old contrails detected near ice saturation, we find similar effective diameters D_{eff} (5.2–5.9 μm), but differences in particle number densities n_{ice} (162–235 cm^{-3}) and in vertical contrail extensions (120–290 m), resulting in large differences in contrail optical depths τ (0.25–0.94). Hence larger aircraft produce optically thicker contrails.

Based on the observations, we apply the EULAG-LCM model with explicit ice microphysics and in addition the Contrail and Cirrus Prediction model CoCiP to calculate the aircraft type impact on young contrails under identical meteorological conditions. The observed increase in τ for heavier aircraft is confirmed by the models, yet for generally smaller τ . An aircraft dependence of climate relevant contrail properties persists during contrail lifetime, adding importance to aircraft dependent model initialization. We finally derive an analytical relationship between contrail, aircraft and meteorological parameters. Near ice saturation, contrail width $\times \tau$ scales linearly with fuel flow rate as confirmed by observations. For higher saturation ratios approximations from theory suggest a non-linear increase in the form $(\text{RHI}-1)^{2/3}$. Summarized our combined results could help to more accurately assess the climate impact from aviation using an aircraft dependent contrail parameterization.

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1 Introduction

Aircraft contrails affect climate by reflection of incoming solar radiation and trapping of outgoing terrestrial radiation. Thereby the global net effect results in a warming of the atmosphere (Fahey et al., 1999). A common metric for the quantification of the climate impact from contrails is the contrail radiative forcing (RF), the difference of the radiative fluxes at the tropopause of two atmospheric scenarios with and without contrails. Minnis et al. (1999) derived a best estimate of the contrail radiative forcing from air traffic in 1992 to 20 mWm^{-2} based on an analysis of traffic data, meteorological data and satellite observations. Lee et al. (2009) extrapolated previous estimates of contrail radiative forcing to the 2005-airtraffic as of 11.8 mWm^{-2} (90 % likelihood range: $5.4\text{--}25.6 \text{ mWm}^{-2}$). Recently, Voigt et al. (2011) estimate a radiative forcing of linear shaped contrails of 15.9 mWm^{-2} ($11.1\text{--}47.1 \text{ mWm}^{-2}$) using extended in-situ observations. The total climate effect of contrail cirrus including linear and persistent contrails is likely larger and may range from 30 to 80 mWm^{-2} (Burkhardt and Kärcher, 2011). Schumann and Graf (2013) derive a global net RF of about 50 ($40\text{--}80$) mWm^{-2} from observations and models for a shortwave/longwave RF-magnitude ratio of 0.6 with possibly larger net RF for smaller ratios. Hence contrail cirrus globally contribute with $\approx 3\text{--}5\%$ to the total anthropogenic radiative forcing of 1.6 Wm^{-2} (Solomon et al., 2007). Local effects can be significantly larger (Burkhardt and Kärcher, 2011; Graf et al., 2012) and the level of scientific understanding is still assessed as low to very low (Lee et al., 2009). The climate impact of contrails depends on contrail cover and optical depth (Meerkötter et al., 1999) and many other solar and earth radiation, microphysical and atmospheric parameters, part of which are aircraft dependent.

The altitude range where contrails form is mainly controlled by ambient temperature and humidity and by aircraft fuel properties (water vapor emission index and specific combustion heat) (Schumann, 1996), with a weak influence of the overall propulsion efficiency of the aircraft/engine combination (Schumann, 2000; Schumann et al., 2000). At the high relative humidity during contrail formation, the engine exhaust plume con-

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tains an aerosol of non-volatile (mainly soot) and volatile particles from condensing particle precursors (sulphuric acid, organic acids) and part of this aerosol gets activated and liquid droplets form which then freeze and form ice particles (Kärcher and Yu, 2009). Ice nucleation takes place in the exhaust jets within a wing-span behind the aircraft or earlier, depending on ambient temperature. Later during the jet phase, depending on aircraft parameters, the airflow above the wings transforms into a counter-rotating vortex pair (Paoli et al., 2003), in which the exhaust material behind each engine is entrained (Gerz and Ehret, 1997). The two vortices propagate downwards by mutual induction of velocity, and take most of the exhaust material with them. The air in the vortex core is heated by adiabatic compression (Greene, 1986). This heating decreases the relative humidity, eventually resulting in a partial sublimation of the ice crystals. During downward movement a fraction of the exhaust is detrained from the vortex pair and parts may propagate upwards by buoyancy to the original emission level, thereby mixing with the exhaust that has not been captured by the vortex pair and building a secondary wake regime. Under ice supersaturated conditions the detrained ice particles grow further by uptake of ambient water vapour (Unterstrasser and Sölch, 2010). Ice crystal number densities and sizes can vary in the primary vortices and the secondary wake (Gayet et al., 2012). After the break-up of the vortex structures, initiated from small disturbances by the Crow-instability or from ambient turbulence (Misaka et al., 2012), the contrail spreads out and disperses depending on atmospheric wind shear and turbulence (Jensen et al., 1998). Contrails may survive for several hours in ice supersaturated conditions (Graf et al., 2012), with the total contrail cover being dependent on air traffic movement and distribution. The contrail life time depends further strongly on the microphysical properties of the contrail particles. Hence, contrails depend on many atmospheric and aircraft parameters, which are known to different degree.

Microphysical and dynamical properties of contrails at various ages have been measured and modeled in several studies (Heymsfield et al., 2010). In-situ measurements in young contrails are challenging because of strong turbulence in the aircraft wake.

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However such measurements provide insight about ice particle concentrations, ice particle sizes, and ice particle habits as required to derive the optical extinction of light (Petzold et al., 1997; Baumgardner and Gandrud, 1998; Poellot et al., 1999; Schröder et al., 2000; Gao et al., 2006; Voigt et al., 2010; Jones et al., 2012). Optical depths of 0.15 and 0.25 have been derived from measurements in two 10 and 20 min old Embraer-170 contrails (Febvre et al., 2009). At an age of 3 min at ice supersaturated conditions the contrail had an optical extinction of 0.48 km^{-1} . Voigt et al. (2011) derived a mean (median) contrail optical depth of 0.27 (0.13) from 14 young < 5 min old contrails near ice saturation of 9 different aircraft. Satellite observations of contrail optical depth concentrate on older contrails (Iwabuchi et al., 2012) as the detection efficiency for young contrails with widths less than few 100 m is limited.

Lidar observations combined with numerical studies by Sussmann and Gierens (1999, 2001) suggest that early contrail properties depend on atmospheric conditions as well as on the aircraft type. While a clear separation of the primary and secondary wake has been detected in the contrail of a four-engine aircraft with the secondary vortex becoming persistent in most cases, this separation has not been observed for two-engine aircraft. Lewellen and Lewellen (2001) calculate the sensitivity of the fraction of the surviving ice crystals, the total ice crystal surface area and the ice mass distribution on the aircraft type and ambient RHI. Naiman et al. (2011) perform large eddy simulations to investigate the influence of meteorological parameters and aircraft type on contrail optical depth and coverage, with variation of the aircraft type resulting in variations in optical depth between 20 % to 50 % with respect to the baseline. Simulations by Unterstrasser and Sölch (2010) show, that contrail evolution in the vortex phase affects contrail optical properties and the lifetime of contrail-cirrus over hours.

While several modeling results suggest an aircraft effect on contrail formation, atmospheric variability has previously prevented a direct comparison of contrail properties from different aircraft. Here we investigate in detail 3 data sequences from in-situ observations in 2 min old contrails from A319-111, A340-311 and A380-841 aircraft detected on 19 November 2008 under similar meteorological conditions with the research aircraft

Falcon above northern Germany during the CONCERT campaign (Voigt et al., 2010). Differences in particle size distributions, number densities, contrail vertical depth and optical depth are evaluated. We compare the results to two model studies performed with the Lagrangian particle tracking model EULAG-LCM (Sölch and Kärcher, 2010) and the contrail cirrus prediction model (CoCiP) (Schumann, 2012) to identify the aircraft influence on contrail properties under identical meteorological fields. The CoCiP model will also be used to show that the contrail properties in young contrails (of order 2 min) are of importance for the climate impact of contrails over the whole life time of the contrails. We analytically derive a relationship between aircraft parameters, meteorological parameters and critical cloud microphysical parameters. We find that the fuel consumption per unit flight path linearly scales with the total extinction, the product of contrail optical depth and horizontal width. We further parameterize the dependence of the total extinction on RHI based on approximations from theory. We compare our findings to our observations and previous measurements and model results.

2 Instrumentation

During the CONCERT campaign the DLR research aircraft Falcon-20E5 was equipped with a set of instruments to measure microphysical and optical contrail properties together with some chemical properties (Voigt et al., 2010). A description of the instrumentation is given in Voigt et al. (2010), individual instruments are discussed in detail by Jurkat et al. (2010), Schmale et al. (2010), Kübbeler et al. (2011) and Gayet et al. (2012). Here, we only describe instruments of relevance for this work.

2.1 The forward Scattering Spectrometer Probe FSSP-300

The forward scattering spectrometer probe FSSP-300 (Baumgardner et al., 1992; Petzold et al., 1997) mounted in the right wing station of the Falcon detects the amount of light scattered by a single particle in forward directions at angles from 6° to 15°. Thereby

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the amount of scattered light depends on the particle size, shape and refractive index. The signal is resolved into an array of 31 channels, which have been calibrated prior to the flight. For the calibration, monodisperse polystyrene latex spheres have been used to calibrate the channels detecting particles $\geq 1 \mu\text{m}$. The smaller size channels were calibrated using sebacate oil droplets. The signal is then converted into a corresponding particle size using the refractive index of $1.31 + 0.0i$ of ice. We assume all ice particles in the young contrails have a quasi-spherical shape. This simplifying hypothesis is confirmed by comparing FSSP-300 results to polar nephelometer (PN) observations in the A380 contrail (Gayet et al., 2012). Best agreement between the extinction derived with 2 independent methods is achieved assuming initially quasi-spherical ice crystals and the fraction of non-spherical particles increasing with contrail age. At contrail ages < 2 min, 80 to 100 % of the particles are quasi-spherical (Gayet et al., 2012, their Fig. 5). In the case of existing non-spherical particles the derived surface areas might be overestimated (Borrmann et al., 2000), however this effect is expected to be small for young contrails.

In the current study channels 1 and 9 are excluded due to instrumental noise and channels 30 and 31 are excluded due to overcounting effects caused by high ice particle concentrations in young contrails. The channels 10–15, 16–18, 19–21, 22–23, 24–25, 26–29 are grouped in order to avoid ambiguities in the probe response function due to Mie scattering theory (Baumgardner et al., 1989). This results in 13 binned size channels for particle diameters between $0.49 \mu\text{m} < D < 17.97 \mu\text{m}$. Uncertainties in the FSSP-300 data are caused by errors in the particle sizing and uncertainties in the number concentration at low sampling statistics or very high particle concentrations. The optical sampling area of our instrument was 0.188 mm^2 , leading to a sampling volume of 38 cm^3 at a typical aircraft speed of 200 m s^{-1} . The number concentration in the contrail is typically in the order of several 100 cm^{-3} and each contrail is sampled and averaged for more than 60 s, therefore errors due to counting statistics are small for $D < 10 \mu\text{m}$. For particle number concentrations less than 500 cm^{-3} , which is higher than the observed particle number concentrations, the errors due to coincidence losses

are below 5 % (Baumgardner et al., 1992). This is supported by the agreement of the extinction derived by FSSP and measured by the polar nephelometer (Gayet et al., 2012) also at high particle number concentrations.

As discussed by Voigt et al. (2011) our FSSP-300 was not equipped with techniques to correct for artificially enhanced ice crystal concentrations caused by shattering of large ice crystals on protruding probe inlets (McFarquhar et al., 2007). Still, the contrails were observed in clear sky or subvisible cirrus, hence large particles were present at very low concentrations, if at all. The comparison to cirrus observations nearby suggests that the ice crystal concentration in contrails is affected by less than 1 % by ambient cirrus (Voigt et al., 2011, their Fig. 2). A similar analysis has been performed for the present study.

2.2 The polar nephelometer

Additionally, the Falcon was equipped with a Polar Nephelometer (PN) (Gayet et al., 1999) mounted on the left wing station. The PN measures the scattering phase function of cloud particles which intersect a collimated laser beam ($\lambda = 804 \text{ nm}$) near the focal point of a parabolic mirror. For very small particles the sampling efficiency is low due to small optical active surfaces (Gayet et al., 2012), therefore only ensemble values can be measured by a longer integration interval. Under the assumption of randomly orientated, non-absorbing ice particles, also integrated optical parameters such as extinction coefficient and asymmetry parameters can be calculated (Gayet et al., 2002). The accuracy of the extinction is 25 % (Gayet et al., 2012).

2.3 Hygrometers

Water vapour mixing ratios were simultaneously measured by the closed path Fast In situ Stratospheric Hygrometer FISH and the frost point Hygrometer CR-2 (Buck Research Instruments, LLC). The instrument FISH was developed at the Research Center Jülich and is based on the Lyman- α photofragment fluorescence technique with a mea-

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surement frequency of 1 Hz (Schiller et al., 2008; Kübbeler et al., 2011). In combination with a backward facing inlet only gas phase water vapor was sampled inside and outside of ice clouds. For the calculation of the relative humidity the air temperature T is needed. The temperature measured onboard of the Falcon is used. The uncertainties are ± 0.5 K for temperature, ± 0.5 hPa for pressure, $\pm 6\%$ or at least $0.3 \mu\text{mol mol}^{-1}$ for water vapor mixing ratio, yielding an overall uncertainty of $\approx 10\%$ for the conditions of this study. The water vapor mixing ratios measured by the CR-2 were generally in good agreement with the measurements by FISH during the CONCERT contrail flights (Gayet et al., 2012).

2.4 The NO and NO_y chemiluminescence instrument

Aircraft exhaust plumes can be identified in in-situ measurements by enhancements in NO and NO_y mixing ratios (Schulte et al., 1997). NO and NO_y are measured with the chemiluminescence technique using two separate rear facing inlets. In the rear facing inlets, particles larger than $0.5 \mu\text{m}$ are stripped from the sampling air due to inertia, and predominantly gas phase NO_y is measured (Meilinger et al., 1999). NO_y is catalytically reduced to NO in a gold converter heated to 300°C using CO as reducing agent. Finally, the chemiluminescence reaction of NO with O₃ is detected. The NO_y instrument has an accuracy of $\pm 10\%$ for NO and $\pm 12\%$ for NO_y (Voigt et al., 2008). With the NO_y instrument, also the uptake of HNO₃ in contrail ice crystals has been investigated (Schäuble et al., 2009).

3 Contrail chasing and meteorology

The meteorological situation over Germany on 19 November 2008 was influenced by a high pressure system located over the Atlantic northwest of France and a low pressure system over northern Scandinavia. Cold and humid air with cirrus clouds was

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advected over Germany in a northern flow and expanded towards the east during the day. The contrails were probed at altitudes near or above the cirrus top.

Three contrails from the A319, A340 and A380 aircraft were visually observed during the flight (Fig. 1). The Falcon pilots descended/ascended into the contrails for in-situ measurements and profiled the contrails at different positions with respect to the contrail axis. In the data sets (Fig. 2), contrails were identified by a simultaneous increase of the NO mixing ratio ($\text{NO} > 0.15 \text{ nmol mol}^{-1}$) and the particle number concentration ($> 0 \text{ cm}^{-3}$ for $D > 2.8 \mu\text{m}$). To investigate an impact of the aircraft type on contrail properties, we selected observations performed under similar ambient conditions (see Table 1) and at similar contrail age (80–118 s). The corresponding age was calculated from the difference between the position of the contrail producing aircraft and the Falcon taking measured wind speeds into account (Jurkat et al., 2011). In the contrail sequences, mean RHI of 91 % (A319), 94 % (A340) and 92 % (A380) were identified from the measurements. Ambient RHI was 94 % for the A319 contrail and slightly higher than inside the contrail. Similar RHI (94 %) have been observed inside and near/above the A340 and the A380 contrails, and slightly lower values below (see discussion by Gayet et al., 2012). Analysis data from ECMWF show lower temperatures along the flight path. For 0.5 K lower temperatures, the RHI may actually be close to ice saturation (98 % to 101 %) and still within the range of instrumental uncertainties of $\pm 10\%$ in RHI.

Table 1 summarizes meteorological conditions and aircraft properties in 3 contrail sequences, which were selected according to similar contrail age and RHI. In addition, the fuel flow, engine type, Mach number, aircraft registration and weight were reported by the pilots, which may lead to limited uncertainties. The NO_x emission index (EI_{NO_x}) was determined as in (Döpelheuer and Lecht, 1999) based on aircraft and engine type and the fuel flow reported by the pilots (with unknown accuracy). For the A380 aircraft the reported fuel flow of $4.75 \text{ t (h engine)}^{-1}$ was reduced by 30 % to match expected fuel flow records (Jurkat et al., 2011).

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4 Particle properties in the A319, A340 and A380 contrails

4.1 Mean particle size and surface area distributions

Particle size and surface area distribution of 80 to 118 s old contrails from A319, A340 and A380 aircraft are shown in Fig. 3. Ambient cirrus ice crystals did not significantly disturb the particle size distributions of the young contrails (Fig. 3a, grey line). Vortex dynamics and wind shear lead to strong variations in the particle concentrations in contrails (e.g. Sussmann and Gierens, 2001). To obtain a representative particle size distribution, it is necessary to perform measurements at various positions in the contrail. As the contrail is heterogeneous on small scale, we assume that after more than 60 s (12 000 m flight path) of contrail probing, our averaged particle size distribution is representative in terms of variability inside the contrail. In the following, we first list the observed contrail properties of the A319, followed by the A340 and the A380. The observed aircraft differ significantly in size and at the time of observation the pilots report aircraft weights of 47/150/508 Mg for the A319/A340/A380, respectively. The particle size distributions of the 3 contrails from the A319, A340 and A380 aircraft have similar effective diameters D_{eff} of 5.2 μm , 5.8 μm and 5.9 μm , which are equal within the instrumental uncertainties. Yet the observed particle number density n_{ice} ($D > 0.93 \mu\text{m}$) increases with increasing aircraft weight from 162 cm^{-3} to 235 cm^{-3} (Table 2).

The projected planar ice crystal surface area A_p of the contrail size distribution (Fig. 3b) also increases for heavier aircraft from 0.93×10^3 to $1.45 \times 10^3 \mu\text{m}^{-2} \text{cm}^{-3}$ in our case. It is dominated by particles in the diameter range 2.8 μm to 12.9 μm . This size range accounts for $\approx 95\%$ of the total ice particle surface area in the 3 contrails.

The vertical profile of the A380 contrail probed at a mean contrail age of 122 s is shown for reference in Fig. 4. NO and ice particle number densities are enhanced over the vertical contrail depth of at least 270 m. At least the upper part of the primary vortex has been probed, indicated by high NO mixing ratios and high particle concentrations. Strong turbulence made the pilots to ascend into the secondary wake soon during this

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observation sequence. Interestingly, the particle number concentrations are enhanced also in the secondary wake in the same order of magnitude as in the primary wake.

4.2 Contrail optical depth distributions

The optical and microphysical properties are calculated according to Schumann et al. (2011). We calculate the extinction coefficient using

$$\beta = \int Q_{\text{ext}}(D) A_p(D) n_p(D) dD \quad (1)$$

with the extinction efficiency Q_{ext} , the mean projected particle cross-sectional area A_p , the number of ice particles n_p and the diameter D . The integral is computed by a discrete summation over all grouped channels of the FSSP-300. The extinction efficiency Q_{ext} has been calculated for each size bin using Mie theory for an optical wavelength of 550 nm. Q_{ext} shows the well-known Mie oscillations for particle diameters in the order of the wavelength and approaches 2 for larger particles.

The distributions of extinction and optical depth τ are calculated from the high frequency (1 s) particle size distribution measurements and the estimated vertical depths of the contrails. The normalized probability density function of contrail extinction is shown in Fig. 5a.

An overview of the mean macrophysical, microphysical and optical contrail properties is given in Table 2. Mean extinctions are increasing from 2.1 to 3.2 km⁻¹ with aircraft weight. The vertical depth of the contrails is deduced based on calculations with the P2P model (Holzäpfel, 2003) for atmospheric conditions prevailing during the flights. The P2P model calculates the sinking distance of the primary vortices. We assume that the contrail develops between the flight altitude of the contrail producing aircraft and the primary vortices structure. Thereby the sinking distances of the vortices and the detrainment of ice particles out of the vortices control the vertical contrail depth. The depth values depend on weight, speed and wing span of the individual aircraft and, in addition, on the meteorological situation, in particular the thermal strati-

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fication (Holzäpfel, 2006). The calculated contrail depths are in agreement ($\pm 20\%$) with contrail dimensions derived from maximum vertical distance between the contrail producing aircraft and the Falcon during contrail observations.

The optical depth is derived from the product of the extinction coefficients and the depth of the wake. We find contrail optical depths of 0.25, 0.55 and 0.94 for the A319, A340 and A380 aircraft (Table 2), suggesting that heavier aircraft produce optically thicker contrails under similar meteorological conditions. The assumption that the mean extinction coefficient is representative for the whole depth of wake may lead to upper bounds. The contrail optical depth distribution is shown in Fig. 5b. The slight dip in the frequency distribution of contrail optical depth of the A380 aircraft could be an effect of low sampling statistics in the contrail optical depth range near 1. The larger vertical thickness of contrails of heavier aircraft caused by the stronger descent of the vortices contributes significantly to the increase in contrail optical depth. In addition also enhanced particle number densities yield higher particle surface areas for larger aircraft.

We also calculate the fraction of the contrail ice water content IWC, which originated from the engine exhaust itself. Assuming NO_y as an inert tracer in the 2 min time scale from engine exit to contrail encounter, the dilution of the engine emissions in the young contrails can be calculated using EI_{NO_x} and the mean observed NO_y values. If water and later ice were similarly diluted and assuming that all of the water emitted by the aircraft had been taken up by contrail ice particles, we calculate the fraction of aircraft water emissions to the observed ice water contents in the contrails. We find that less than 10 % of the contrail ice particles originate from the aircraft exhaust water in the 2 min old contrails, suggesting that ice supersaturation prevailed during contrail growth.

5 Model simulations and results

The evolution of contrails in the vortex phase is influenced both by aircraft parameters and the atmosphere. Allowing identical meteorological conditions, in contrast to obser-

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vations, model simulations may be used to study contrail evolution influenced only by different aircraft types. We perform numerical simulations of the evolution of contrail properties in the vortex phase with two independent models, the EULAG-LCM model system (Sölch and Kärcher, 2010) and the CoCiP model (Schumann, 2012). This way we can separate the aircraft effect from atmospheric variability and gain a better insight and understanding of the observed results. Moreover, we will test the sensitivity of contrail RF to the properties of young contrails.

5.1 Cloud resolving model study

5.1.1 The EULAG-LCM model system

The EULAG-LCM model (Sölch and Kärcher, 2010) is a large-eddy model based on the inelastic numerical solver for geophysical flows EULAG (Grabowski and Smolarkiewicz, 2002). The model was originally designed to study the formation and evolution of natural cirrus clouds and recently used to study the evolution of contrails in the vortex phase (Unterstrasser and Sölch, 2010). A combined Eulerian/Lagrangian approach is used to simulate the evolution of the contrail ice crystals and their interaction with the wake dynamics with the help of the microphysical module LCM. Water vapour and trace gases are treated similar to the dynamical and thermodynamical variables in a fixed Eulerian grid. In contrast, the ice phase is treated by tracking a large number of simulation ice particles (SIP) in the flow field. Each SIP represents a number of real ice crystals with identical properties. We calculate the depositional growth or sublimation of ice crystals by interaction with water vapour, their gravitational sedimentation, and turbulent dispersion on ice crystal trajectories. Ice formation, aggregation, and radiative processes are excluded in the model runs as these are of minor importance for contrail physics in the vortex phase. Effects of buoyancy of the exhaust plume due to a higher initial temperature in the exhaust plume are not considered directly, but the effects are represented by additional small scale turbulence added to the aircraft wake.

5.1.2 Atmospheric conditions and contrail initialization

For analysis of the influence of the aircraft type on the contrail evolution and resulting optical depth, the evolution of the contrails of the A319 and A380 are simulated in a three dimensional domain, with horizontal extensions of $256\text{ m} \times 400\text{ m}$ and 256 m and 512 m in vertical extent, with 1 m resolution, initialized as given in Table 3. Atmospheric profiles of temperature and pressure are specified on the base of the observation. As the profile of RHI at the time of contrail formation is not known precisely, we assume a constant profile over height at model initialization. Any horizontal variability in flight direction is not resolved in the small LES domain. The model atmosphere is stably stratified with $N = 0.012\text{ s}^{-1}$, similar to observational values. We superimpose a grid scale ambient turbulence field (mean eddy dissipation rate of $\varepsilon = 6.25 \times 10^{-5}\text{ m}^2\text{ s}^{-3}$) onto the model domain, generated with a separate LES simulation to match the reported turbulence level. At initialisation we assume that the vortex roll-up process is fully completed and impose two counter-rotating vortices with a Lamb-Oseen profile of tangential velocity and an initial circulation according to Table 3. The initial circulation strength Γ_0 is calculated from the reported mass, airspeed and wing span of the aircraft at the time of the measurements. We start the simulation at a contrail age of 20 s and introduce the contrail's ice crystals inside two circles around the vortex cores with jet area radii r_0 (see Table 3), with a spatially uniform crystal distribution. Different geometrical assumptions on the initial distribution may alter resulting ice crystal concentrations up to 10% . The number of ice crystals per meter of flight path N_0 is estimated with assumed soot emission indices. $\text{EI}_{\text{soot}} = 0.323 \times 10^{15}\text{ (kg}^{-1}\text{ fuel)}$ and $\text{EI}_{\text{soot}} = 0.236 \times 10^{15}\text{ (kg}^{-1}\text{ fuel)}$ are chosen for the A319 and A380, respectively, being representative estimates for regional and large aircraft (Eyers et al., 2004, their Table 31), based on engine calculations of Döpelheuer (2002). The values are in good general agreement with the few measurements of soot emission of cruising airliners with different engines ($1.8\text{--}6 \times 10^{14}$) (Anderson et al., 1998; Petzold et al., 1999; Schumann et al., 2002) and with the decrease of soot number emission indices for younger

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engines (Petzold et al., 2005). It is assumed that each emitted soot particle forms an ice crystal, which should be reasonable for low fuel sulphur contents (Schumann et al., 2002). Hence, the initial ice crystal numbers depend on engine type and fuel flow. If the initial ice crystal number would be higher, more particles with a smaller mean radius would form, as the total IWC would remain the same due to unchanged El_{H_2O} and atmospheric supersaturation. This would lead to initially larger extinction and optical depth values due to larger particle surfaces. However, with contrail aging more particles would sublime, especially in the primary vortex, so for higher contrail age the extinctions may become reduced. The absolute effect of larger initial ice crystal numbers also depends on the atmospheric background conditions. Finally, we assume that the initial ice crystals contain exactly the amount of the water vapour emitted from the engines. In each grid box the ice crystal size distribution is supposed to be log-normal (Unterstrasser and Sölch, 2010). Overall, we track more than 70×10^6 (236×10^6) SIP, each representing on average 10 300 (16 000) ice particles, respectively.

5.1.3 Calculation of the evolution of the A319 and A380 contrail under identical meteorological conditions

We model the evolution of the contrails of an A319 and an A380 aircraft with the EULAG-LCM model (Sölch and Kärcher, 2010) with atmospheric parameters shown in Table 4. As discussed above, the observed contrails must have experienced local ice supersaturation in the first minutes of their lifetimes in order to explain the high ice water contents in the observations. In addition, a growth of ice particles has been observed in the A380 contrail (Gayet et al., 2012). This indicates that ambient air was close to saturation or even supersaturated. Hence background relative humidity was set to 97 % and 103 % in different model runs, respectively, which is at the upper limit of observations but still within the instrumental uncertainties. For the case of $RHI = 103\%$, further model evaluation to assess both horizontal and vertical extension of the contrail and the fraction of the surviving ice crystals has been performed for the A319 and A380.

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A special procedure is used to compute particle size distributions averaged along the plume for comparison with observations. The exact measurement position relative to the vortex centres is unknown since the contrail was deformed by local wind and turbulence. Therefore, the model results were averaged along simulated linear flight paths. Linear flight paths were randomly chosen as horizontal lines through the model grid with a randomly chosen starting point. Virtual flight paths that did not include any simulated ice particles were excluded from the analysis, similar to the criteria applied to the observational data. A total of 16 300 (19 700) simulated particle size distributions were recorded for the A319 (A380) aircraft, respectively.

The mean particle size distributions and planar projected surface distributions obtained for A319/A380 for RHI = 97 % with respect to ice are shown in Fig. 6a and b and particle number concentration for particles > 0.5 μm and effective diameter are given in Table 4. In addition, the measured particle size distribution in the A319 contrail is shown for comparison. Both observations and model results show an increase in ice number density for heavier aircraft and similar particle size distributions for both aircraft. However the modelled ice size distributions have slightly lower effective diameters compared to the observations. For large particles ($D > 10 \mu\text{m}$), the simulated particle number density deviates significantly from observations. This deviation cannot be explained using higher RHI in the simulation, as predominantly particle losses after contrail formation in the wake are reduced so that the total particle number density at the time of measurements is enhanced at higher RHI (see Fig. 7).

In addition we investigate the impact of RHI on ice crystal size distribution in contrails. An increase in the atmospheric background relative humidity to 103 % has a strong impact on contrail parameters such as ice number density n_{ice} and contrail optical depth (Table 4) in the simulation results. n_{ice} is reduced in subsaturated conditions due to sublimation of particles at the lower end of the size distribution. Effective diameters are nearly unchanged and vary by < 10 % for 97/103 % RHI. At higher ice supersaturation, D_{eff} increases due to enhanced water uptake on the ice.

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A large discrepancy between the observation and the modelling of an A380 aircraft has been found regarding the evolution of a secondary wake. While during observation, large numbers of ice particles are found in the secondary wake (see Fig. 4), no significant number of ice particles is apparent in the model at A380 flight altitude at $t = 100$ s. We can exclude ice crystal sublimation in the simulation due to $\text{RHI} > 100\%$ in most regions. Perhaps not all ice particles formed during the jet phase are mixed into the vortices but create a visible secondary wake, especially for four-engined aircraft. Particle detrainment may be still underrepresented in the EULAG-LCM model. Slightly different atmospheric conditions may lead to different vortex dynamics and enhanced detrainment of ice particles. Because of strong dilution at an initial plume age of 20 s, the model is initialized with constant temperature. Buoyancy from still warm exhaust gases inside the plume could increase the detrainment.

In the case of the modelled A319 contrail, larger fractions of ice particles are detrained from the primary vortices than for the modelled A380 contrail. Due to lower aircraft weight and smaller wing span, the primary vortices of the A319 have already decayed further at a contrail age of 100 s. Due to the breakup of the vortices the warmed detrained air can rise upwards again buoyantly and cause mixing extending the ice particle distribution. This feature develops later for the A380 contrail in the model. The two particle size distributions observed in the primary and secondary wake of the contrail of the A380 aircraft are shown in Fig. 8. While the total particle number is similar for both contrail segments, particles tend to be much larger in the secondary wake leading to higher values for extinction and contrail optical depth. The optical depth distribution depends strongly on the mean vertical contrail extension, which is dependent on the formation of a secondary exhaust plume.

Mean values for the extinction of 1.4 km^{-1} (3.4 km^{-1}) for the A319 aircraft and 1.7 km^{-1} (2.6 km^{-1}) for the A380 aircraft are calculated for 97 (103)% RHI, respectively. The model results of the extinction are in good agreement with the observations. However, the extinction decreases for the A380 with respect to the A319 due to stronger particle sublimation in the primary wake, whereas particles can grow in the secondary

wake, which is more distinct for the modelled A319 contrail. The optical depth is derived directly for the case of 103 % RHI from the model using the calculated contrail extension. The optical depth is calculated to be 0.09 for the A319 contrail and 0.16 for the A380 contrail. The optical depth still increases for the heavier aircraft, but both values derived by the model calculations are significantly lower than those derived by the observational data.

This discrepancy can be only partially explained by higher RHI values. The underrepresentation of large particles ($D > 7 \mu\text{m}$) in the model also contributes to this effect. The discrepancy is higher for the A380 aircraft as the underrepresentation of large particles is more distinct (see Fig. 3) and because of the limited development of an ice particle containing secondary wake at $t \approx 100 \text{ s}$.

5.2 Bulk model study

5.2.1 The model CoCiP

The contrail properties can be estimated using a bulk ice cirrus model as implemented in CoCiP (Schumann, 2012). The model is based on the following assumptions: all contrail parameters are assumed to be uniform over an effective contrail cross-section of area A . All processes are assumed to occur isobaric and temperature changes due to phase changes are assumed to be negligible. The properties in the measured contrail are assumed to result from a mixture of N_{dil} mass units of ambient air with the emissions resulting from burning one mass unit of fuel. By definition, the dilution ratio relates any mass specific concentration Δc of passive tracers in the exhaust plume to its emission index EI by $\Delta c = EI/N_{\text{dil}}$. The humidity q inside the contrail is assumed to be at ice saturation. The ice mass in the contrail results from the humidity from entrained ambient air plus the amount of water emitted from the aircraft after approaching ice saturation. The number of ice particle is taken as proportional to the number of soot particles emitted times an estimated ice particle survival factor f_s . The survival factor accounts for particle losses during vortex sinking. The dilution ratio N_{dil} that CoCiP

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computes for given aircraft properties, plume age, and thermal stratification, is sensitive to ambient shear which is not well known from the observations. Therefore, here dilution is instead estimated from the measured ΔNO_x (or ΔNO_y) concentration excess above ambience.

- 5 For these conditions, the contrail cross-section area A , in m^2 , follows from the dilution ratio N_{dil} (Schumann et al., 1998),

$$\rho A = N_{\text{dil}} m_F \quad (2)$$

with ρ = air density, and m_F the fuel consumption per flight distance in kg km^{-1} . The ice water content IWC, in kg m^{-3} , is

$$10 \text{ IWC} = \text{El}_{\text{H}_2\text{O}} m_F / A + \rho(q_0 - q_{\text{sat}}), \quad (3)$$

with $\text{El}_{\text{H}_2\text{O}} = 1.23$, water vapour emission index for kerosene, A the contrail cross-section area in m^2 , q the absolute humidity or water mass mixing ratio in kg kg^{-1} , q_0 the ambient humidity.

- 15 The saturation mixing ratio for ice saturation, $q_{\text{sat}} = (M_{\text{H}_2\text{O}}/M_{\text{air}})p_{\text{ice}}(T)/p$, is a function of p , the ambient pressure in Pa, $p_{\text{ice}}(T)$ the ice saturation pressure and T , the ambient air temperature in K, and the molar vapour/air mass ratio $M_{\text{H}_2\text{O}}/M_{\text{air}} = 0.622$. The number of ice particles per flight distance N_{ice} and the volume specific particle concentration n_{ice} are

$$N_{\text{ice}} = f_s \text{El}_{\text{soot}} m_F, n_{\text{ice}} = N_{\text{ice}} / A, \quad (4)$$

- 20 with the soot particle number emission index El_{soot} and f_s the survival factor. The volume mean particle size r_{vol} , in m, follows from

$$N_{\text{ice}} \rho_{\text{ice}} (4/3) \pi (r_{\text{vol}})^3 = \text{IWCA}. \quad (5)$$

Here, ρ_{ice} is the ice particle bulk density in kg m^{-3} (assumed: 917 kg m^{-3}). The optically effective radius r_{eff} differs from r_{vol} . The ratio is the factor C as discussed in

$$r_{\text{eff}} = r_{\text{vol}}/C. \quad (6)$$

The factor ranges typically from 0.6 to 1 and can be determined for the measured cases from the measured values of IWC, number density and effective radius:

$$C = [\text{IWC}/(\rho_{\text{ice}} N_{\text{ice}} \pi 4/3)]^{1/3}/r_{\text{eff}}. \quad (7)$$

The radiation extinction coefficient is

$$\beta = 3Q_{\text{ext}} \text{IWC}/(4\rho_{\text{ice}} r_{\text{eff}}), \quad (8)$$

with $Q_{\text{ext}} = 2$ (or a size-dependent value) as radiation extinction efficiency.

The optical depth over an effective contrail depth H is

$$\tau = H\beta \quad (9)$$

For weak ambient shear, the width of the contrail B is of order $(\pi/2)s$, where s is the span width of the aircraft (in agreement with Misaka et al. (2012), see below). The effective contrail depth H and contrail width B are related to the contrail cross-section area $A = BH$. For given contrail cross-section area and given B , effective contrail depth H results.

The so-called total extinction is

$$EA = B\tau = A\beta. \quad (10)$$

Finally, one can insert the above equations to obtain a closed solution for the dependence of EA on aircraft and meteorological parameters:

$$EA = [9\pi/(16\rho_{\text{ice}}^2)]^{1/3} C Q_{\text{ext}} m_F [f_s \text{EI}_{\text{soot}}]^{1/3} [\text{EI}_{\text{H}_2\text{O}} + (\text{RHI} - 1) N_{\text{dil}} M_{\text{H}_2\text{O}} p_s(T)/(M_{\text{air}} p)]^{2/3} \quad (11)$$

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for given $RHI = q/q_{\text{sat}}$. Hence, the total extinction $EA = A\beta$ scales linearly with both the optical properties CQ_{ext} of the contrail particles and with the fuel consumption per flight distance m_F . In addition it scales with the third root of the number of ice particles surviving per unit mass of burnt fuel, and the 2/3 root of an expression containing $El_{\text{H}_2\text{O}}$ and $(RHI-1)$, basically the ice water content in the plume per flight distance normalized to fuel consumption. The latter scales with dilution N_{dil} in ice-supersaturated air, ambient relative ice supersaturation $(RHI-1)$, temperature T (because of the saturation pressure $p_s(T)$) and the altitude-dependent inverse ambient pressure p . The contributions from water vapour engine emissions (measured by $El_{\text{H}_2\text{O}}$) may be important for short-lived and sublimating contrails but negligible for large dilution in ice-supersaturated air. Aircraft parameters enter this equation mainly by the fuel consumption, the emission index for soot, flight level (ambient pressure), and the aircraft dependence of the dilution. Meteorology enters in terms of temperature, humidity, and ambient parameters controlling dilution N_{dil} (wind shear, thermal stratification, ambient turbulence). Cloud microphysics and wake dynamics are important for C , Q_{ext} and the survival factor f_s .

5.2.2 CoCip model results and comparison to observations

The analysis uses input values as listed in Table 1. From the measurements we expect the bulk results for relative humidity RHI , NO_y excess ΔNO_y , ice water content IWC , and effective particle diameter D_{eff} as listed in Table 2. The data imply $C = 0.87$, 0.77 and 0.73 , for the three cases. In the following we use $C = 0.8$.

The model results depend critically on the assumed dilution value N_{dil} . In particular, NO_y mixing ratio and particle concentrations become small and the contrail evaporates early for subsaturated conditions when the dilution factor is large. The dilution value N_{dil} expected from interpolating previous measurements can be calculated via $N_{\text{dil}} = 7000(t/1\text{ s})^{0.8}$ for the given plume ages t . It would be about 0.30×10^6 for the A319 and A380 aircraft and 0.24×10^6 for the younger A340 aircraft. The interpolation is known to have about a factor of three uncertainty (Schumann et al., 1998). The measured NO_y

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values suggest larger dilution values of 1.33×10^6 , 1.40×10^6 , and 1.94×10^6 for the A319, A340 and A380 aircraft. On the other hand, smaller particle concentrations result for larger dilutions values. Based on the assumed emission index for NO_x and the initial number of ice particles being assumed as emitted soot particles, either the measured NO_y concentration is a factor 5 too low or the measured particle concentrations are a factor 5 too high for consistent dilution modelling of NO_y and particles. At present, this discrepancy is an open issue.

For best consistency in ice particle properties, the results in Table 5 are computed for small dilution values implying five times higher NO_y mixing ratios than measured. Still, even with the factor 5 reduced dilution values (implying higher exhaust concentrations), the contrail fully evaporates when the observed conditions (see Table 1) apply constantly over the whole contrail life time. Larger RHI values are required for consistency of the bulk model and the clearly visible contrail.

5.2.3 Comparison to EULAG-LCM model results

We applied the CoCiP bulk model with the small dilution values also to the assumed RHI values of 97 and 103 % used for the EULAG-LCM model (see Table 5). Both models compute a visible contrail also for a slightly subsaturated environment (97 %). The computed numbers for ice particle concentration and effective diameters are of the same order of magnitude. The NO_y concentration in the EULAG-LCM model is slightly lower compared to CoCiP implying larger dilution factors. The effective diameters of ice particles are similar in the EULAG-LCM and the bulk model. The ice particle number density in EULAG-LCM is higher than in the bulk model for the A380. For the A319, the ice particle number density in EULAG-LCM is lower than in the bulk model. The vertical extension calculated by EULAG-LCM is low due to limited formation of the secondary wake in the case of the A380. The dilution dependent vertical extension in the bulk model is somewhat higher. The calculated optical depths values agree well between EULAG-LCM and the bulk model.

5.2.4 Importance of aircraft dependence of contrail properties for radiative forcing

CoCiP is also used in a simulation of global contrail cover to compute the radiative forcing (RF) by contrails. Since contrail cirrus modelling is difficult, these results should be seen as a qualitative indication of the importance of the aircraft impact on contrails. Moreover, the simulation was performed for a three-day period only. The global simulation with this model shows a change of net RF by factors of 0.73 or 2.51, when the global fleet of aircraft is replaced by a fictive fleet in which all aircraft are either A319 or A380 aircraft, respectively. Hence, the RF is about a factor 3.5 larger for an A380 than for an A319, because of larger aircraft mass (factor 8), larger fuel consumption (factor 6), and related soot emissions and size dependent mixing in the aircraft wake. In terms of RF per passenger-seat or RF per passenger-seat-distance, the ratio is closer to unity or even smaller than one, i.e., a larger aircraft may have smaller climate impact per transport unit than a smaller aircraft. This shows the importance of knowing the climate impact of contrails as a basis for selecting the proper aircraft for the respective transport task.

6 Impact of fuel flow on contrail optical properties

The observed optical and microphysical properties of the three young contrails are in the range of earlier observations. Lidar measurements by Sussmann and Gierens (2001) report a maximum optical depth of 0.26 for a 5 min old contrail from the research aircraft Falcon at RHI = 111 %, which is in the range of the optical depth derived for the A319 aircraft. The observed extinction coefficients of the contrails are about a factor of 4 higher than previously observed by Febvre et al. (2009) for contrails from a comparatively small Embraer-170 aircraft of similar age. A maximum ice particle number concentration of $420/580/540 \text{ cm}^{-3}$ was observed in the 2 min old A319/A340/A380 contrails, which is slightly lower than observations in a less than 1 min old B757 con-

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trail (Baumgardner and Gandrud, 1998), probably due to increased dilution. The ice particle number concentrations in the 3 contrails agree well with number concentrations of several 100 cm^{-3} with D_{eff} between $4\text{ }\mu\text{m}$ and $8\text{ }\mu\text{m}$ in a less than 3 min old contrail reported by Schröder et al. (2000).

In order to scale optical contrail properties to unit flight distance, we integrate the extinction over the vertical ellipsoidal contrail cross section (results see Table 6), whereby the contrail depth is derived from the P2P model (Holzäpfel, 2006) and the contrail width from Misaka et al. (2012) (their Fig. 23). Misaka et al. (2012) performed large eddy simulations to analyse the development of the contrail vertical and horizontal extension with regard to different atmospheric conditions. For typical ambient temperature stratification and no or weak atmospheric turbulence, represented by their cases 1–3, the plume width of a passive tracer is nearly constant at a value of $1.9\text{ }b_0$ in the first minutes of contrail evolution, with b_0 being the initial vortex spacing. Assuming an aerodynamic favourable elliptic lift distribution, b_0 can be estimated by $\pi/4$ times wing span of the aircraft. The plume width is close to the estimate $B = (\pi/2)\text{ }s$ used in the bulk model (see above).

Interestingly, for 2 min old contrails near ice saturation, the total extinction EA, that is extinction integrated over contrail cross section, shows a linear dependence on the fuel flow rate (Fig. 9). The observational data of EA versus fuel flow rate m_F can be fitted by with a slope of $5.6\text{ (m km kg}^{-1}\text{)}$ and a R^2 of 0.989 (standard error of 0.41) (see also Table 5). This is fully consistent with bulk model calculations (see Eq. 11), shown in Fig. 9. The absolute values in the bulk model simulations are smaller than in the observations, as discussed above. The extinction measured by the PN is lower than the extinction derived from the FSSP-300. This can be explained by the assumption in data analysis that all particles are spherical at the time of measurement, to enable a comparison between the contrails. During contrail aging particles typically grow more aspherical. However, the difference is still small in young contrails and the differences between PN and FSSP-300 are within the measurement uncertainties. Additionally, bulk model simulations for 130 % RHI are shown. For comparison, results

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from Naiman et al. (2011), Sussmann (1999) and Febvre et al. (2009) are shown in Fig. 9, although the atmospheric conditions and aircraft properties differ significantly from our cases. Naiman et al. (2011) calculated the contrail optical depth and contrail width for different aircraft fuel flow rate at 130 % RHI with an initial ice crystal number per fuel burnt of 10^{15} kg^{-1} , and for fixed aircraft fuel flow rate at changing RHI (110 %, 120 %, 130 %). The computed contrail width was about 80/100/60/80/80 m, and optical depths about 1.0/1.5/0.75/0.55/0.75 for their contrail cases E/F/G/M/L, respectively (their Fig. 16). The reported total extinction was calculated assuming an ellipsoidal contrail cross section, as in this study. The simulation results also show a linear increase of contrail total extinction with fuel consumption at 130 % RHI, although the absolute values are higher due to higher ice supersaturations. For 110 % RHI the simulation results are close to our observations. Sussmann (1999) observed a 50 s old contrail from a B747–400 aircraft (weight 345 Mg) with a lidar instrument. Ambient RHI is unknown, but ice supersaturated conditions are expected because of observed particle growth in the secondary wake. The total extinction shown is based on an estimated optical thickness of 0.45 (their Fig. 8) and a contrail width of a B747–400 aircraft of 96 m, calculated analogue to the contrail widths in this study. The observations by Febvre et al. (2009), with assumed 50 m contrail width and 120 m vertical extension, are in good agreement with the EULAG-LCM model results, but lower than observed for the A319 in this study.

7 Discussion

A dependence of contrail properties on aircraft type has been modelled previously (Lewellen and Lewellen, 2001; Unterstrasser and Gierens, 2010; Naiman et al., 2011). Sussmann and Gierens (2001) use model results in combination with Lidar observations to discuss contrail properties in relation to the number of aircraft engines. Here, we use state of the art in-situ observations in combination with results from two independent models, the EULAG-LCM model (Sölch and Kärcher, 2010) and the CoCiP model (Schumann, 2012) to investigate the dependence of contrail properties in air-

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craft size, weight and fuel flow. In the models, the initial atmospheric conditions are kept constant, while parameters depending on the aircraft type such as wing span, weight, speed, fuel flow, and soot emission index are changed. The observed increase of ice crystal number and contrail optical depth with increasing aircraft weight is confirmed with the EULAG-LCM model, although details depend strongly on ambient humidity, as expected. The bulk model also computes an increase in optical depth but lower ice particle concentrations compared to the observations. In addition, we find no significant differences in particle sizes of 2 min old contrails from different aircraft both in the observations and in the models.

Both models underestimate the ice crystal number density in the secondary wake outside the primary vortices, particularly for the A380 aircraft at $t = 110$ s. This might be an effect of complex turbulent mixing processes, which are a challenge to be accurately represented in models. We may speculate, especially in the case of a 4-engine aircraft, that not all ice particles are entrained into the primary wake, leading to a formation of an initial secondary wake structure containing ice particles. Also, the soot emission index used to assume an initial ice crystal number in the models is a rough estimate. Larger initial ice crystal numbers leading to higher ice crystal number densities in the contrail are possible. In addition, there is a discrepancy in the representation of large particles ($D > 10 \mu\text{m}$) between observations and EULAG-LCM model results. This may give hints to an inaccurate representation of the initial ice crystal size distribution in the model. Also instrumental oversampling or over-sizing of low particle concentrations at the large size end of the FSSP-300 sampling range may have contributed to the differences. However, ice particles larger than $13 \mu\text{m}$ contribute less than 5 % to total surface area, hence these few large particles are of minor importance for optical contrail properties which are dominated by the high particle number densities in the size range 3 to $13 \mu\text{m}$. The relevant size range may increase for higher ambient humidity and temperatures.

The dependence of contrail properties on ambient RHI is significant in both models. The bulk model suggests that the total optical depth increases with $(\text{RHI}-1)^{2/3}$ for large

dilution values and for constant other properties. The measured ambient RHI was increased by $\sim 7\%$ in order to synchronize the model results with the observed ice water contents. This value is still within the range of instrumental uncertainties of the humidity and temperature measurements. At higher ambient RHI (110 % in the EULAG-LCM model), the computed particle diameters and optical depths increase by stronger water vapour uptake but still do not reach the observed sizes. Overall, the measurements and simulations show differences with respect to relative humidity and particle sizes, which could be investigated in more detail in future aircraft campaigns.

A comparison of the EULAG-LCM and the CoCiP model shows that the bulk model gives results which are at the same order of magnitude as the detailed, process-oriented EULAG-LCM model. Both models compute a visible contrail for a slightly ice subsaturated environment (97 %). The calculated effective particle diameters are similar in the EULAG-LCM and the bulk model. In addition, the ice particle number density in EULAG-LCM is similar to the bulk model, and dependent on aircraft size. The bulk model suggests an increase of total extinction with $[N_{\text{dil}} (\text{RHI}-1)]^{2/3}$ for higher supersaturation and large dilution, when the contribution from the emitted water has become small. Hence, further contrail evolution is largely influenced by dilution (wind shear, ambient stratification and ambient turbulence) and ambient RHI fields. Changes in microphysical contrail properties will then occur and will change the factor CQ_{ext} which depends on particle habit and size distribution (Schumann et al., 2011). The further evolution also depends on formation and loss of ice particles, i.e. the effective survival factor. The aircraft effects on contrail properties remain notable at least up to contrail ages of tens of minutes Lewellen and Lewellen (2001) and Naiman et al. (2011), and influence the characteristics of contrail cirrus on even longer time scale (Unterstrasser and Sölch, 2010).

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8 Conclusions and outlook

In-situ observations of contrail properties were used to investigate the dependence of contrail properties on the aircraft type. Contrails with ages less than 2 min from A319-111, A340-311 and A380-841 aircraft were probed with the research aircraft Falcon during the CONCERT2008 campaign under similar meteorological conditions (pressure, ambient RHI, temperature, stable stratification, low shear). An increase in ice particle number density and contrail vertical depth is observed with increasing aircraft weight, yielding a factor of 3 higher optical depths for the heavier aircraft (τ range 0.25 to 0.94). Interestingly, effective particle diameters of the 3 contrails were similar within the experimental uncertainties at RHI near ice saturation.

Simulations with two independent models were used to investigate the dependence of contrail properties on aircraft size. In the models, the initial atmospheric conditions are kept constant while aircraft dependent parameters are chosen to match the observed cases. The increasing trend in ice crystal number density and contrail optical depth with increasing aircraft weight is confirmed by the model results, yet generally for smaller τ , possibly due to underrepresented turbulent mixing processes in the models. The contrail properties also show a strong dependence on ambient RHI, as expected. A CoCiP simulation shows large effects in global contrail radiative forcing for model initializations with two fictive fleets of A319 or A380 type aircraft only, suggesting a sensitivity of contrail parameters to the aircraft type throughout the contrail life time. An analytical formulation is derived from the bulk model, see Eq. (11). It explains the observed dependence of contrail properties on aircraft type by higher fuel consumption per unit flight distance of the larger aircraft and therefore higher emissions particularly of water vapour and soot. In addition, a deeper descent of the vortices and therefore a larger contrail extension contributes significantly to the increase in contrail optical depth. The total extinction (extinction \times contrail cross section) scales linearly with the fuel flow per flight distance in model simulations and observations. A non-linear dependence on RHI is predicted by the bulk model. Further observations in contrails at

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higher ambient relative humidity and in aged contrails would be helpful to confirm the dependence of the total extinction on aircraft and atmospheric parameters. Such relationships would be important as input for detailed contrail models. They might also be used to initialize contrail parameters in regional and global models without resolving the small-scale contrail dynamics in the wake vortex period, as the aircraft type and fuel flow are often given in aircraft emission inventories.

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Table 1. Conditions for a subset of observations selected to investigate the impact of the aircraft type on contrail properties. Encounter time and contrail altitude are given for the complete contrail encounters, the other values correspond to the selected contrail sequences. Pressure, temperature, reactive nitrogen (NO_y) mixing ratio and relative humidity with respect to ice (RHI) have been measured on board the Falcon. The fuel flow rate (m_F) was reported by the pilots of the commercial aircraft. The contrail age and NO_x emission index ($\text{NO}_x = \text{NO} + \text{NO}_2$) have been calculated as detailed in the text. The fuel sulfur content has been measured for the A319 and A340 aircraft.

Aircraft	A319-111	A340-311	A380-841
Encounter time (UTC)	09:14–09:27	08:45–08:48	12:14–12:29
Contrail altitude (km)	10.5–10.7	10.5–10.7	10.3–10.7
Pressure p (hPa)	241	242	241
Temperature T (K)	217	217	218
Brunt-Väisälä Frequency	0.0170	0.0126	0.0132
NO_y (nmol mol^{-1})	4.3	4.4	6.7
EI_{NO_x} (g kg^{-1})	8.7	11.6	19.7
RHI (%)	91	94	92
Contrail age (s)	105–118	80–90	102–115
Fuel flow (t (engine h)^{-1})	0.9	1.3	3.6
Fuel flow rate (kg km^{-1})	2.2	6.4	15.9
Aircraft engine	CFM56-5B6/P	CFM56-5C2	Trent 970-84
Mach	0.76	0.737	0.85
Fuel sulfur content (mg kg^{-1})	1155	940	–
Aircraft weight (Mg)	47	150	508
Wing span (m)	34.09	60.30	79.81

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Table 2. Microphysical, macrophysical and optical properties of the selected contrail sequences from A319, A340 and A380 aircraft, derived from FSSP-300 measurements. Mean particle number density ($D > 0.93 \mu\text{m}$), effective diameter D_{eff} , projected planar surface area A_p , ice water content IWC, vertical extension and optical depth τ are given for the 3 aircraft.

Aircraft	n_{ice} (cm^{-3})	D_{eff} (μm)	Projected surface area A ($\mu\text{m}^2 \text{cm}^{-3}$)	IWC (mg m^{-3})	Extinction (km^{-1})	Vertical extension (m)	Optical depth τ
A319	162 ± 18	5.2	$0.93(\pm 0.14) \times 10^3$	$4.1(\pm 1.0)$	$2.1(\pm 0.3)$	120	0.25
A340	164 ± 11	5.8	$1.12(\pm 0.17) \times 10^3$	$4.0(\pm 1.0)$	$2.9(\pm 0.4)$	220	0.55
A380	235 ± 10	5.9	$1.45(\pm 0.22) \times 10^3$	$5.2(\pm 1.3)$	$3.2(\pm 0.5)$	290	0.94

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Table 3. Initialization and settings of the EULAG-LCM model for the contrail simulations.

Domain	A319	A380
Grid Cells	256 × 400 × 256	256 × 400 × 512
Grid spacing	$\Delta x = \Delta y = \Delta z = 1 \text{ m}$	
Time steps	$\Delta t = 0.04 \text{ s}$	$\Delta t = 0.02 \text{ s}$
Total time	120 s	
Atmosphere		
Stability	$N^2 = 1.44 \times 10^{-4} \text{ s}^{-2}$	
Eddy dissipation rate	$\varepsilon = 6.25 \times 10^{-5} \text{ s}^{-3}$	
Ice saturation ratio	$S_i = 0.97$	
Wake properties		
Initial circulation	$\Gamma_0 = 197.61 \text{ m}^2 \text{ s}^{-2}$	$\Gamma_0 = 652.9 \text{ m}^2 \text{ s}^{-2}$
Number of ice particles per flight distance	$N_0 = 0.072 \times 10^{13} \text{ m}^{-1}$	$N_0 = 0.378 \times 10^{13} \text{ m}^{-1}$
Jet radius	$r_0 = 12 \text{ m}$	$r_0 = 22 \text{ m}$
SIP	70×10^6	236×10^6

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Table 4. Parameters used in the EULAG-LCM model and model results. Extinction, optical depth τ , effective diameter D_{eff} , particle number density n_{ice} and the ice crystal survival factor are calculated with the EULAG-LCM model simulating the observation process. Results for assumed initial RHI of 97 % and 103 % are shown. NO_y values are calculated under the assumption of NO_y being a passive, non-reactive tracer. Initial NO_y values are calculated by using EI_{NO_x} (Table 1) and assuming that all NO_y is trapped within the vortex at 20 s contrail age.

	unit	A319	A319	A380	A380
RHI	%	97	103	97	103
Pressure p	mbar	241	241	241	241
Temperature T	K	217	217	217	217
Contrail age	s	100	100	100	100
EI_{soot}	10^{14} kg^{-1}	3.23	3.23	2.36	2.36
NO_y mixing ratio	nmol mol^{-1}	11.4	11.4	20	20
Ice water content IWC	mg m^{-3}	1.1	1.593	1.4	1.92
Ice particle concentration n_{ice}	cm^{-3}	92	217	166	372
Effective diameter D_{eff}	μm	3.82	3.58	3.42	3.26
Vertical extension H	m	–	54.1	–	60.1
Horizontal extension B	m	–	36.9	–	86.7
Optical depth τ		–	0.09	–	0.16
Mean extinction β	km^{-1}	1.3	1.7	1.7	2.4
Survival Factor at 100 s		–	0.72	–	0.69

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Table 5. Parameters used in the CoCiP bulk model and model results, in a presentation similar to Table 4.

	unit	A319	A319	A380	A380
RHI	%	97	103	97	103
El _{soot}	10 ¹⁴ kg ⁻¹	3.23	3.23	2.36	2.36
NO _y mixing ratio	nmol mol ⁻¹	21.5	21.5	33.5	33.5
Ice water concent IWC	mg m ⁻³	1.2	2.3	0.6	1.8
Ice particle concentration n_{ice}	cm ⁻³	234	234	117	117
Effective diameter D_{eff}	μm	2.8	3.4	2.8	4
Vertical extension H	m	28	28	128	128
Horizontal extension B	m	53.6	53.6	123.3	123.3
Optical depth τ		0.04	0.06	0.09	0.19
Mean extinction β	km ⁻¹	1.4	2.1	0.70	1.5

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Table 6. Contrail properties, total extinction and fuel consumption per unit flight path for 3 different aircraft.

Aircraft	Vertical depth (m)	Contrail width (m)	N_{ice} (m^{-1})	Fuel flow m_F per flight distance (kg km^{-1})	Total extinction (extinction \times contrail cross section) (m)
A319	120	51	7.73×10^{11}	2.2	10
A340	220	90	2.58×10^{12}	6.4	39
A380	290	119	6.39×10^{12}	15.9	88

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Fig. 1. Probing contrails from 3 aircraft (top: A319, middle: A340 and bottom: A380) on 19 November 2008 above Germany. The photos are taken from the cockpit of the DLR research aircraft Falcon. The nose boom of the Falcon is visible in the top photo.

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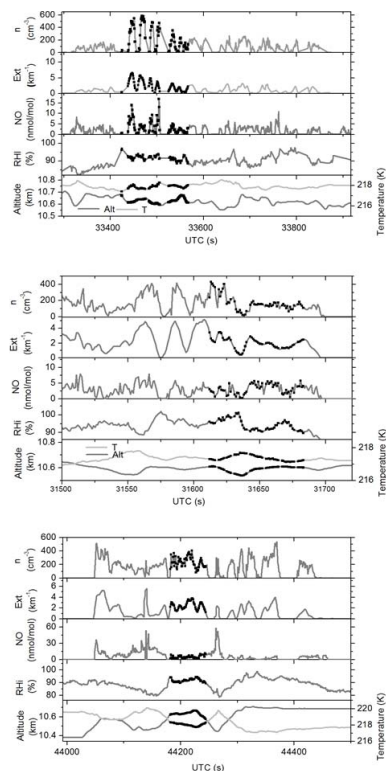


Fig. 2. Time series of contrail observations of the aircraft A319 (top), A340 (middle) and A380 (bottom) as described in Fig. 1. Particle number density n (for diameters $D > 2 \mu\text{m}$), extinction β , RHI, temperature T and flight altitude are shown. Contrail sequences used to investigate the aircraft influence on contrail properties are marked with black squares.

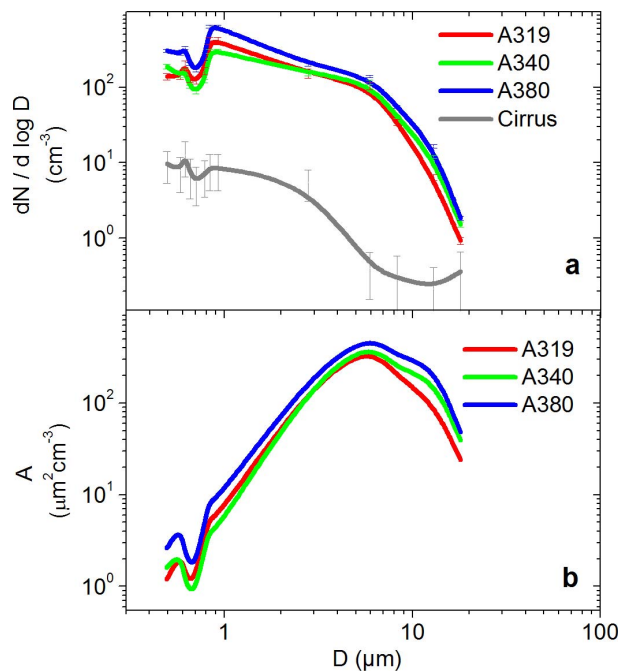


Fig. 3. Particle size distribution **(a)** and projected planar surface area distribution **(b)** of the selected contrail sequences from A319, A340 and A380 aircraft versus particle diameter D . Higher total particle concentrations are observed in the contrails from heavier aircraft (A380: 580 t, A340: 150 t, A319: 47 t), leading also to higher surface area distributions. The maximum in the surface distribution at a diameter near $7 \mu\text{m}$ is dominating the optical properties of the contrails. The error bars correspond to errors in counting statistics and are small due to large particle numbers. In panel **(a)** the particle size distribution of a surrounding cirrus cloud is also shown for reference. Obviously, effects by ambient cirrus clouds on the microphysical contrail properties are negligible.

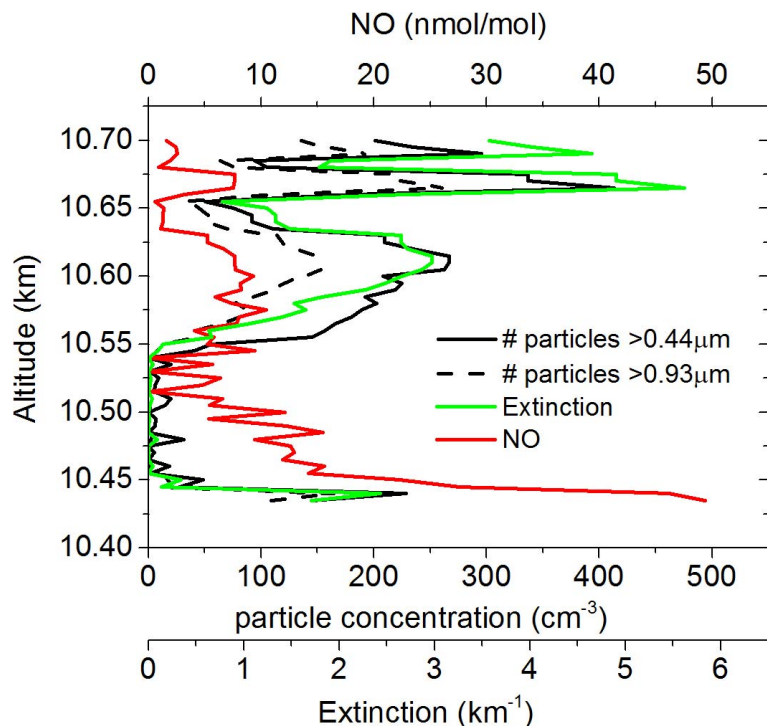


Fig. 4. Profile of the ice particle concentrations for $D > 0.44$ and $D > 0.93 \mu\text{m}$, extinction derived from FSSP data and NO levels in the A380 aircraft case versus altitude. The profile has been recorded in the time between 44 223 s and 44 327 s UTC (see Fig. 2, bottom panel) at a mean contrail age of 108 s. Enhanced particle concentrations and NO mixing ratios are observed over a vertical range of 270 m. The primary vortex has been entered at altitudes below 10.45 km altitude. It may extend further down.

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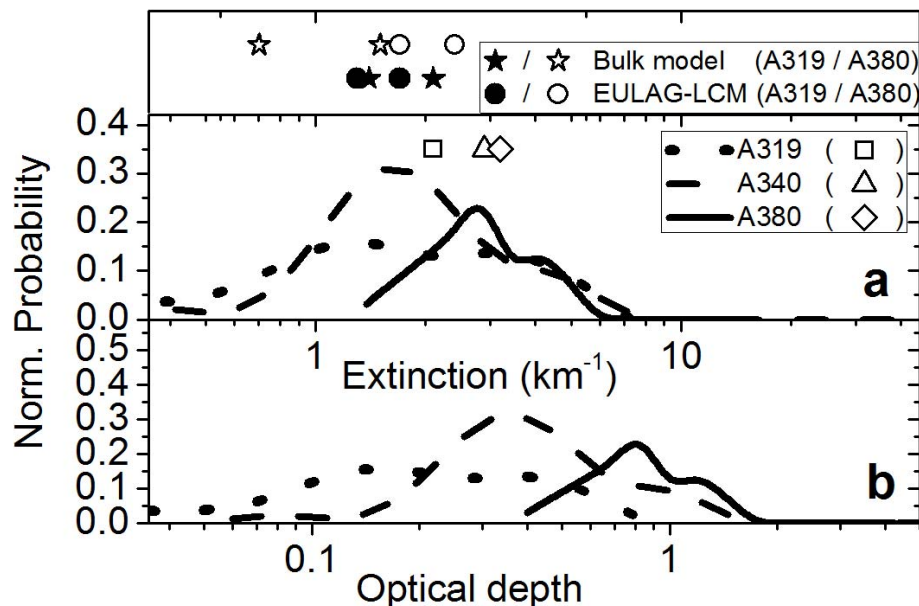


Fig. 5. Normalized frequency distributions of extinction **(a)** and optical depth **(b)** of the selected sequences from A319, A340 and A380 contrails. Mean extinction values of the 3 aircraft are shown in **(a)** in empty symbols. Mean and maximum extinction and optical depth increase with increasing aircraft weight under similar meteorological conditions. For comparison, the mean extinction values derived by EULAG-LCM and the bulk model are shown in the upper panel for the two airliners for 97 % (103 %) ambient RHI, with the lower values for 97 % ambient RHI.

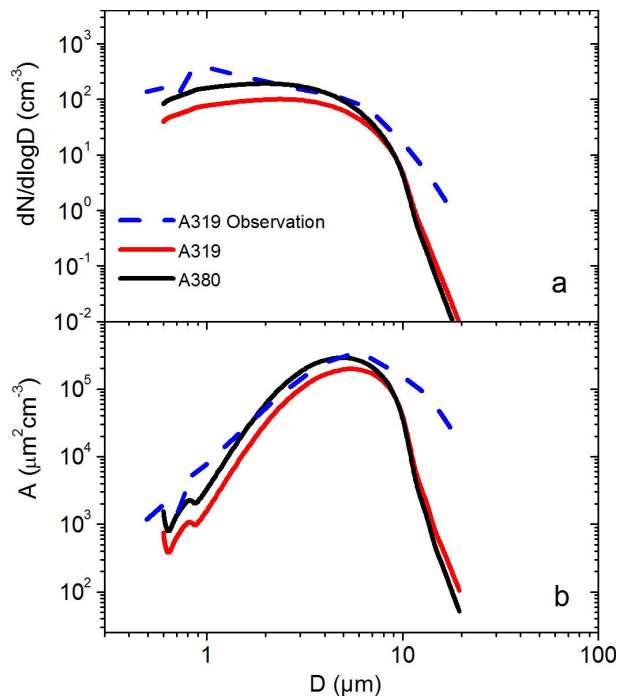


Fig. 6. Average particle size and planar projected surface area distributions from A319 (red) and A380 (black) aircraft contrails calculated with the EULAG-LCM model for ambient RHI 97 %. The dashed blue line corresponds to the observed particle size and surface distribution. The particle size distributions have a similar shape in model and observation for $D < 10 \mu\text{m}$ with significant differences for $D > 10 \mu\text{m}$, with higher total number concentrations in the observation. The optical properties of the contrails are dominated by particles with $D \approx 6 \mu\text{m}$.

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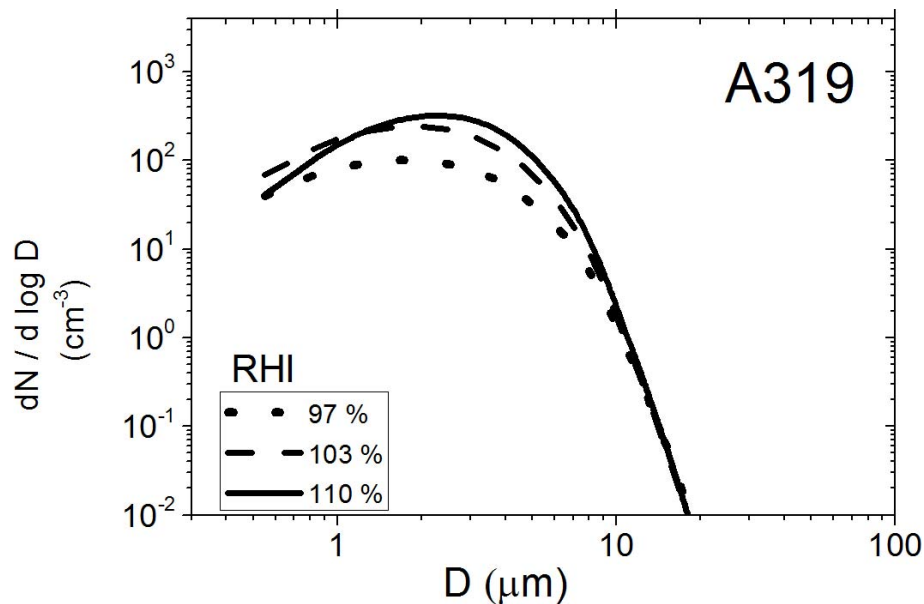


Fig. 7. Particle number concentrations for ambient RH of 97/103/110 %, respectively. The simulations were performed with the EULAG-LCM model for the A319 aircraft. All parameters but RH were kept constant. While the total particle number increases for higher RH, no significant concentration increase is observed for large particles. The increase of article number density with increasing RH for diameters within $1 \mu\text{m}$ to $10 \mu\text{m}$ leads to higher values in extinction and optical depth.

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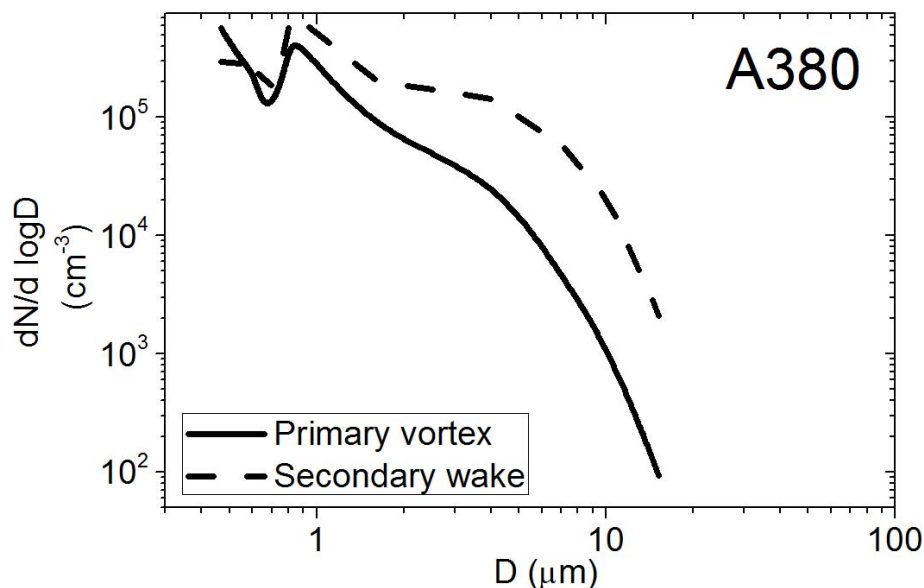


Fig. 8. Particle size distribution observed in the contrail of the A380 aircraft. The secondary wake has been observed between 44 182 s and 44 232 s UTC (see Fig. 2) at a contrail age of ≈ 105 s, the primary vortex has also been observed between 44 112 s and 44 158 s UTC at a contrail age of ≈ 92 s on 19 November 2012. Particle concentrations decrease in the primary vortex due to partial particle sublimation of initially larger ice crystals.

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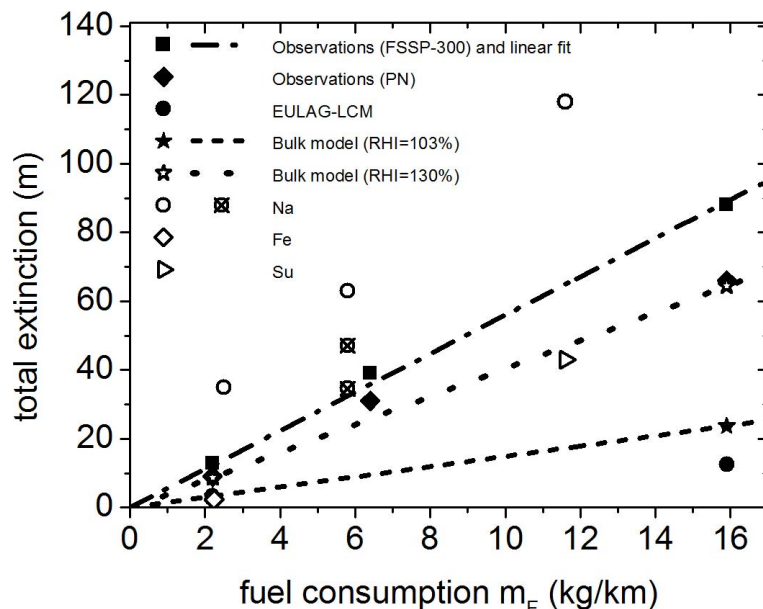



Fig. 9. Total extinction (extinction times contrail cross section) is shown versus the fuel consumption per distance of the contrail producing airliner. Results from this study are shown in bold symbols. A linear fit has been applied to the FSSP-300 observations with a gradient of $5.6 \text{ m (kg km}^{-1})$ (point-dashed line). In addition results from polar nephelometer measurements are shown in bold diamond symbols. Differences between FSSP and PN results are explained by different assumptions on particle shape. The results of the bulk model are shown by the dashed (pointed) line with star symbols fitting the fuel consumption of the analyzed airliners for $\text{RHI} = 103\%$ (130%). For comparison, model results from Naiman et al. (2011) (their Fig. 16) are shown by the empty circle symbols (Na). The contrail age is about 100 s, initial RHI are 130% (empty circles) and $110\%/120\%$ for the crossed circles, with the lower value for 110% . Lidar observations of a 50 s old contrail of a B747 by Sussmann (1999) are shown by the empty triangle symbol (Su). Additionally the total extinction observed in situ by Febvre et al. (2009) for a young and small contrail is shown by the empty diamond symbol (Fe).