Simulation of Contrails in the vortex regime – Examination of the microphysical properties

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ABSTRACT: In the vortex regime the contrail development is governed by the wake dynamics. The major fraction of the ice crystals is trapped inside the downward travelling vortex pair. For ambient supersaturations below a certain threshold, none of the trapped crystals survive the vortex phase. Only crystals detrained during the descent form the contrail. The ambient relative humidity has a strong impact on the vertical extent of the contrail and on the number of surviving ice crystals, especially in the vortex. Contrail development during the vortex regime was modelled with ambient supersaturations ranging from 0% to 20%. The computationally cheap 2D-code permits a large number of simulations. A realistic vortex decay was ensured using parameterisations of 3D-simulations. The obtained results give detailed information on initial states for contrail-to-cirrus simulations.

1 INTRODUCTION

Contrails form when the Schmidt-Appleman criterion is fulfilled (Schumann, 1996). Contrails are persistent when the surrounding air is supersaturated with respect to ice. During the vortex phase the majority of the ice crystals is trapped in the counter-rotating vortex pair and is transported downwards. Inside the descending vortices, adiabatic compression/heating reduces the relative humidity and leading eventually to the sublimation of ice mass (Sussmann and Gierens, 1999; Lewellen and Lewellen, 2001). The final vertical displacement depends on the initial strength of the vortex (aircraft parameter) and on its decay (controlled by meteorological parameters like turbulence, stratification). We identify the parameters which predominantly control the number and the distribution of ice crystals surviving the vortex phase. The main parameter discussed here is relative humidity. Further important parameters are flight level (i.e. temperature), initial circulation, turbulence, stratification, aircraft parameters (their is effect is not discussed here).

2 MODEL DESCRIPTION AND SETUP

The large-eddy simulations have been carried out with the non-hydrostatic anelastic 3D model EULAG (Smolarkiewicz and Margolin,1997) which was supplemented with an ice microphysics code (Spichtinger, in prep). The parameterised microphysical processes are deposition growth/ condensation and sedimentation. The simulations run on a 2D domain. The horizontal direction x is along wingspan and z is the vertical coordinate. The domain has an horizontal/vertical extent of x_D=256m and z_D=500m with 1m-resolution in each direction. The time step is dt=0.02s. The simulations start at the beginning of the vortex phase and end with vortex break-up after 135s. The aircraft properties typical of a large aircraft are implemented (initial circulation Γ_0 = 650 m²/s, wing span bspan=60m). The ice crystals are uniformly distributed in circles (r=20m) around the vortex

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centres. The total emitted water (1.46 10^{-2} kg per m flight path) is contained in the ice crystals (3.4 10^{12} per m flight path). Furthermore, the nucleation of the ice crystals is assumed to be completed during the jet phase and no further nucleation is considered during the vortex phase. The temperature at cruise altitude is 222K. The pressure is p_0=250hPa at the lower boundary. The atmosphere is stably stratified (Brunt-Väisälä frequency $N=10^{-2}s^{-1}$) with an initially constant relative humidity with respect to ice. The supersaturation s_i ranges from 0% to 20%. The eddy dissipation rate is 3.5 10^{-5} m^2 s^{-3}

3 VORTEX DYNAMICS

The decay of the vortex pair depends on meteorological parameters (stratification and eddy dissipation rate) as well as on aircraft parameters (initial circulation Γ_0 and initial vortex separation b_0).
The vortex decay can be divided into two regimes. During the diffusion phase the vortex weakens independently of the latter parameters. After a certain onset time T2 the rapid decay phase sets in.
Generally, time T2 is smaller and the rapid decay is faster for higher turbulence and for stronger stratification. The temporal evolution of Γ in dependence of the parameters mentioned above is given in Holzäpfel, 2003 (see Fig. 1, solid line).
In 2D-simulations the vortex decay is generally too slow as the Crow instability (the most efficient destructive process) is not resolved (see Fig. 1, dashed line). The diffusion coefficient in the simulations is artificially increased around the vortex cores and adapted each second in order to assure a realistic decay. The simulated circulation (see Fig. 1, dotted line) is in good agreement with the values given in Holzäpfel, 2003.

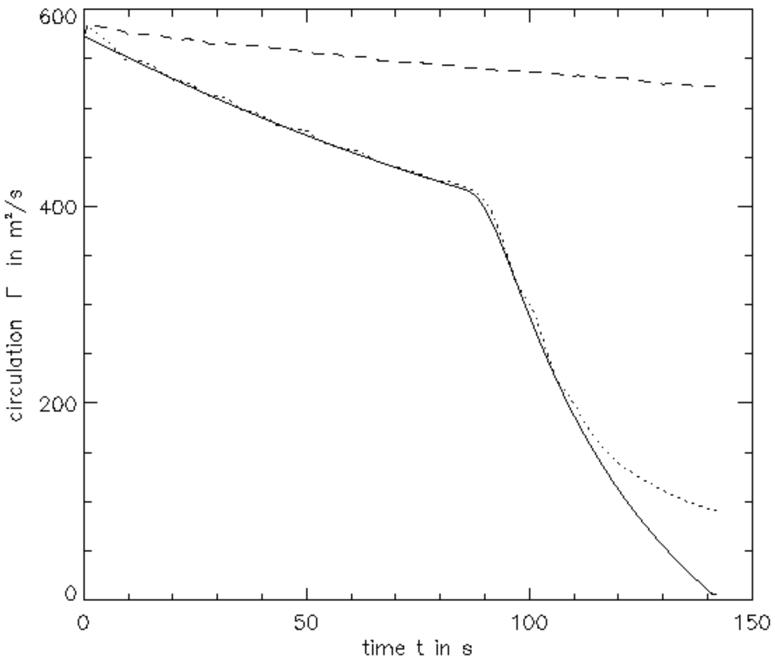

Figure 1: Temporal evolution of the circulation Γ

4 RESULTS

The total ice mass per flight path tIWC [kg/m] is computed with the following integral.

$$tIWC = \iint IWC(x,z)dxdz$$

In order to determine the ice mass contained in the primary wake pIWC, the integral is restricted to 40m-circles around the vortex centres. The area of the secondary wake is one 50m-circle centred at the flight altitude in the middle of the domain (i.e the position that was crossed by the body of the aircraft). The according integral quantity is called sIWC. Analogously, the number of ice crystals in the different areas (tN,pN,sN) is determined. In some figures, the latter quantities are normalised by

the initial ice mass or crystal number, resp. These quantities tell us which fraction of ice mass and crystals is still present after a certain time. In general, the contrail loses a major part of its crystals in the primary wake. At the beginning of the simulation, the areas of the primary and the secondary wake overlap. At later times, there is a vertical gap, as the vortex pair travelled downwards. The amount of ice in the so-called curtain (i.e. the vertical stripe between the vertically displaced vortex and flight altitude) can be determined by tIWC-pIWc-sIWC.
The temporal evolution of the normalised quantities is shown in Figure 2. The temperature at cruise altitude is T_{CA}= 222K and the relative humidity RH_i is 105%.

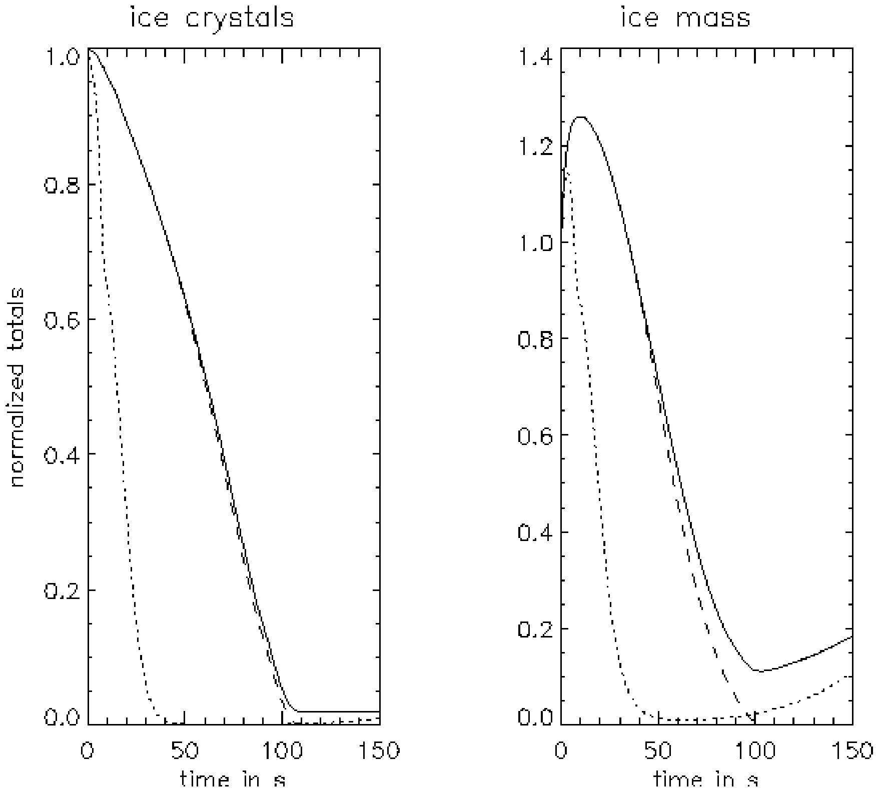

Figure 2: left panel: temporal evolution of the number of ice crystals in the total area tN (solid line),in the primary wake pN (dashed line) and in the secondary wake sN (dotted line). Right panel: Analogously for ice mass. The ambient supersaturation was 5%.

Initially, tIWC increases due to deposition growth of the ice crystals until the excess moisture from ambient supersaturation is consumed. During the downward transport the local RH_i in the vortices decreases due to adiabatic heating and the number of ice crystals declines in the primary wake. Later the minor number of crystals in the secondary wake becomes significant, as these crystals steadily grow. Figure 3 shows the vertical profiles of ice mass and crystals at vortex break-up time t=135s. The profiles are shown for various relative humidities (100%, dotted; 105% dashed; 110% dash-dotted; 120% dash-dot-dotted). Again, the temperature is 222K.
The initial ice crystal distribution was centred around z=400m (solid line). After 135s the vortex pair travelled below z=200m. A substantial fraction of the trapped ice crystals survives only for high supersaturation ($s_i \geq 10\%$). This threshold s_i-value depends on vortex break-up time, descent speed and temperature. It can be concluded that the mean ice crystal mass in the primary wake is smaller than in the secondary wake at the end of the vortex phase. The earlier the crystals are detrained and mix with ambient air, the larger they are. The moister it is, the larger is the vertical extent of the contrail and the more ice crystals survive the vortex phase.

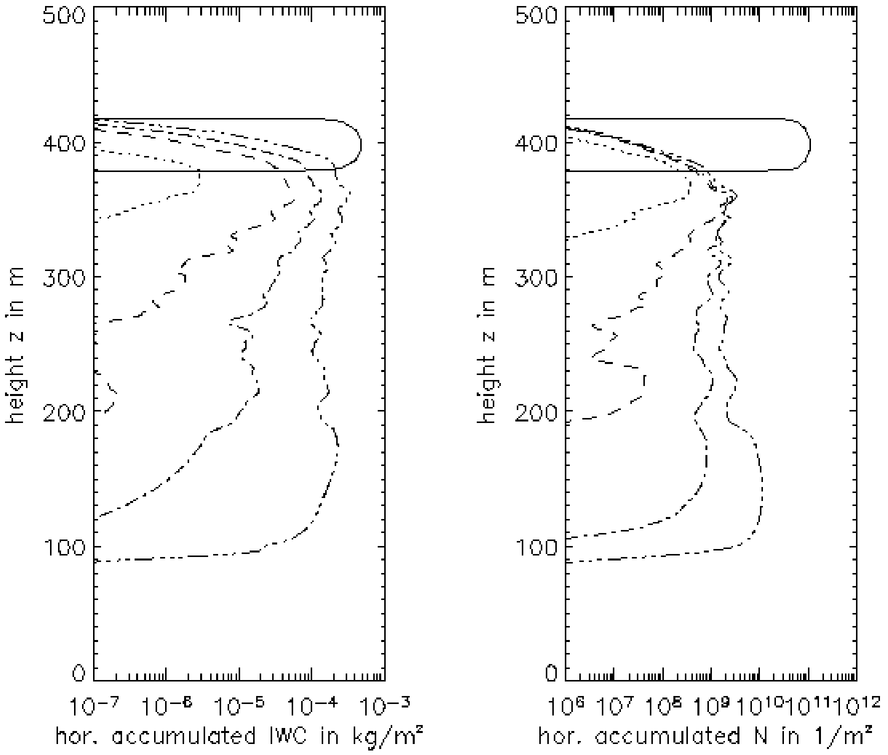

Figure 3: vertical profiles of ice mass (left) and crystals (right) for various supersaturations s_i (0%, dotted; 5% dashed;10% dash-dotted; 20% dash-dot-dotted).

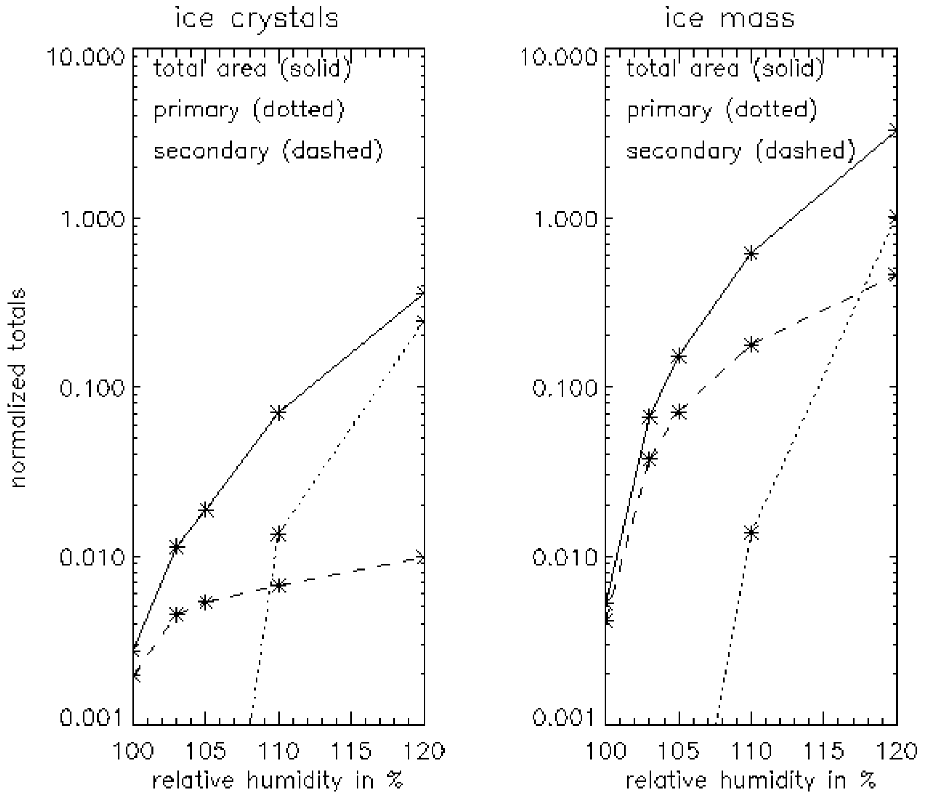

Figure 4 left panel: Normalised totals of surviving ice crystals tN,pN and sN as a function of RH_i. Analogously, the surviving ice mass on the right hand side.

Figure 4 shows the normalised totals of ice mass/crystals at the time of vortex break-up as a function of RH_i. In all cases, the normalised number of surviving crystals is below unity. Not surprisingly, a moister environment is favourable for less ice crystal loss. The normalised tN ranges from 40% at s_i =20% to less than 1% at s_i =0%. The number of ice crystals in the secondary wake sN is

weakly dependent of humidity and nearly all crystals which were not trapped inside the initial vortex pair survive, as long as the ambient relative humidity $RH_i \geq 100$. Generally, the fraction of crystals in the secondary wake increases relative to the primary wake with decreasing supersaturation. The right panel of Figure 4 shows the normalized value of surviving ice mass. It is apparent, that the ice mass in the secondary wake increases with relative humidity, as more excess moisture condenses on the crystals. At high supersaturation a major part of the ice mass is inside the secondary wake, although less than 1% of the crystals are detrained in the beginning.
At vortex breakup time, the total ice mass and number of crystals present as a function of RH_i can be fitted with a power law $a \cdot (RH_i - b)^{\alpha}$.The exponent α is roughly 3 for the present simulations, but it may depend on other meteorological variables.

5 CONCLUSION/ACKNOWLEDGEMENTS

Relative humidity was identified as one key parameter for the microphysical properties of a contrail at the end of the vortex phase. The number of surviving ice crystals grows with supersaturation. In cases with $RH_i \leq 110\%$, the total IWC after 135s was below the initial level. The vertical profile of the ice crystal distribution strongly depends on RH_i and the concentration and the mass of the crystals is different for the primary and secondary wake. Many more parameters (as given in the introduction) can be studied with the existing code. Especially, the variation of temperature has also an major impact on the contrail properties. The presented results will be used as initial states for simulations of the dispersion phase. This will help to understand and simulate the contrail-to-cirrus transformation.
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