Reply to referee 1 - paper acp-2009-394

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1 General comments

We would like to thank you for your insightful comments that helped to improve the paper. As you suggested, we further analyzed the simulation data during the vortex phase in Sec. 3 where we showed the inhomogeneous distribution of the contrail (e.g. in terms of ice crystal number and size) both in the cross-stream and axial directions. The manuscript has been largely rewritten in many parts to address the comments of both referees.

2 Specific comments

Title and Abstract: To avoid misunderstanding with the words 'contrail-cirrus' we changed the title of the manuscript as "Influence of vortex dynamics and atmospheric turbulence on the early evolution of a contrail". Our study covers the vortex and dissipation regimes (up to a a wake age of 30 minutes) when the driving mechanisms for the contrail are the wake vortex dynamics and the atmospheric turbulence. We removed the term "diffusion regime" that is more appropriate to the phase when the contrail transforms into cirrus and processes like radiative heating and sedimentation are effective.

Background: we left out the lines as suggested.

P20431: As mentioned above, the sentence "transient phase to contrail-to-cirrus transition" was badly used. It was referred to all the mechanism (vortex + dissipation in the definition we are using now) we are simulating. We agree that the vortex regime is crucial for determining the particle distribution in the late evolution of the contrail –indeed an important part of our study (Sec. 3) is devoted to it – although the novel part (in terms of proposed model and methodology) is in our opinion the simulation of the interaction of the contrail with the atmospheric turbulence (Sec. 4).

P20433: We corrected. The mechanisms cited here (sedimentation, radiative heating, and wind shear) are mainly responsible for the spreading of the contrail rather than ice growth which is controlled by supersaturation.

P20436: We removed Sonntag's formula. We added a comment at the end of Sec. 2.1: Note that particles are assumed to be always activated (see e.g. [4] for a detailed description of this important process), so Eq. 2 can also be interpreted as a conservation of particle nuclei: sublimation of ice crystals is allowed until the radius shrinks to a minimum value set to $r_m = 20\text{nm}$ (which roughly corresponds to the soot core radius). If supersaturation with respect to water switches to positive values (because of transport of vapor and temperature in the wake) then crystals form (through the classical pathway of vapor condensation into droplets and instantaneous freezing [4]) and ice can start growing again via Eq. 3. Although this very simple treatment of microphysics will be improved in the future, the eventuality of complete sublimation is excluded in the present study because of the high ambient relative humidity [2].

P20437: We mean "feature" = "goal" . Quoting from the new version of the manuscript: "An important goal of the present study is to resolve the combined action of short and longwave vortex instabilities, the baroclinic torque and the atmospheric turbulence."

P20437: We added the initial and final time for each simulation in Tab.1. The basic chain of simulations consists of $VD1$ (vortex and dissipation regimes) and $D1$ (late dissipation regime). Simulations $V0, V1, V2, V3$ only cover the vortex regime ($t < 140$ s). We clarified this point in the Introduction.

P20439: Values of major species obtained from measurements and simulations of internal flows in the engine nozzle were reported e.g. by Ref. [1] : for water vapor the mass fraction was $Y_v^{\text{exit}} = 2\ 10^{-2} kg/kg$. On the other hand, a typical jet core radius can be estimated as $r_j = 0.3\ m$ [3]. This gives an emitted water mass per flight meter $M_v^{ac} = 2.1\ 10^{-3}\ kg/m$. Using an emission index of 1.2 kg/kg, this yields to a fuel consumption rate of 10 kg/km for a four-engine aircraft. The initial ice mass at the beginning of the vortex regime is estimated by assuming that the jet regime can be divided in two steps: first the formation of the ice particles during the first second, and then their entrainment around the vortex (see the sketch in the figure below). At $t = 1\ s$, the conservation of water mass yields

$$\left.(\rho_v^{sat}(T_a) + \rho_i^{Ka})\right|_{t=1s}\ \pi r_{Ka}^2 = M_v^{ac} + \rho_v^{\text{atm}}\ \pi r_j^2 \tag{1}$$

where r_{Ka} is the jet core radius at $t = 1\ s$. We assumed that at $t = 1\ s$, the temperature in the jet is close to the ambient temperature T_a, and that during this first step, no ambient air has been entrained in the jet (*i.e.* r_j is used in the right-hand side term). The ice density ρ_i^{Ka} is estimated from 0D simulations [5]. Mean values of the number density ($n_p = 10^{10}\ m^{-3}$) and the ice particle radius ($r_i = 0.85\ \mu m$) yield $\rho_i^{Ka} = 2.36\ 10^{-5}\ kg/m^3$. Therefore, equation 1 yields to a jet core radius $r_{Ka} = 3.14\ m$ which gives for a quadri reactor a number of particle per meter of flight of $N_p = 1.54\ 10^{12}\ m^{-1}$ (where we use the the mean number density of Ref. [5]. To evaluate initial ice particle radius, we use the

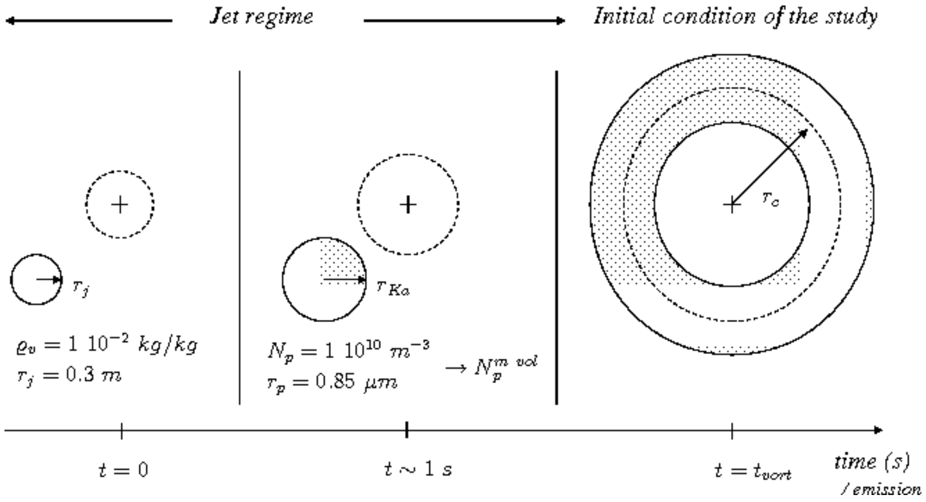

Figure 1: schematic view of the jet regime.

conservation of the water mass over the second step of the jet regime. We assume that at the end of the jet regime, all particles have the same radius, and that the ambient air has been entrained inside the vortex. These considerations yield to a mean ice particle radius of $r_i = 1.5\ \mu m$ at the begining of the vortex phase.

P20422: The term "eventually" can lead to some misunderstanding and has been replaced by "partly" (see above P20436).

Section 3.1:
a & d) From the point of view of vortex dynamics, vortex rings will necessarily dissipate at some point because of the interaction with the background turbulence for example. At a given wake age, the amount of particles trapped in the rings compared to the amount of particles released to the atmosphere at the break-up location is indeed an important question that has been addresses in the new version of the manuscript. We decided to put this discussion in Sec. 3.2 (contrail microphysics) which was largely rewritten. We added three new figures (Figs. 8-11 in the new version) showing vertical profiles of ice mass and averaged number density at different locations along the flight direction and at different wake ages. It gives information on the vertical spreading of the contrail, its local mass variation, as well as its variability along the flight direction.
b) The variation of the density in the cross section is highly non homogeneous. The definition of a diffusion time does not seem to be relevant in this regime.
c) The number of particles in the secondary wake is one order of magnitude smaller than that in the primary wake. However, this fraction can be sensitive to the way the vortex is initially perturbed. Future studies will investigate this point (e.g. using a full turbulent spectrum instead of a single Crow wavelength).
e) We did a mistake on the caption. We inverted left and right panels. About the range of concentration (n_p^{max}/n_p^{min}), we agree that the bulk approach limits this range. Figures

8 and 10 (in the revised version) have been replotted with a clip on the number density limiting the range to 3 order of magnitudes. The largest ice crystals with physical meaning are now about 8 μm. They match the second mode of the PDF from Fig 10.
f) this will be investigated in future study.

P20443–P20444. We corrected and fixed typos.

Figure 1: MesoNH applies a hydrostatic balance on the initial field with no correction on the temperature. This results in a slight perturbation on the potential temperature which is corrected after the first time step when the equation of state is applied through the energy equation.

Figure 14: The red dots have no physical meaning: the (cell-averaged) particle radius is not transported directly but reconstructed in post-processing from ice mass and number density (prognostic variables). As stated above, the figure shows the limits of the bulk approach at late times. This has been mentioned in the caption of the figure. In the future we will improve the model (e.g. by advecting higher moments of the size distribution).

We added the two references.

References

[1] F. Garnier, C. Baudoin, P. Woods, and N. Louisnard. Engine emission alteration in the near field of an aircraft. *Atmos. Environ.*, 31:1767–1781, 1997.

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[3] L. Jacquin and F. Garnier. On the dynamics of engine jets behind a transport aircraft. AGARD CP-584, NATO, 1996.

[4] B. Kärcher. Physicochemistry of aircraft-generated liquid aerosols, soot, and ice particles. 1. Model description. *J. Geophys. Res.*, 103:17111–17128, 1998.

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