Dear Sajedeh,

unfortunately, the reviewer is not satisfied with the new version of the manuscript, as you can see from his last report (attached at the end of the document). The main point of criticism is that in the model the combination of the to ice modes from contrails an cirrus is treated as one mode. The reviewer criticizes that the further development of the cloud does not reflect reality and illustrates this with a simple exemplary calculation:

- the mixed growth rate is about a factor 2.76 larger than for the two mode case. This would lead to a very different time evolution, reducing the supersaturation much faster than in the first case.

- for the mixed mode the resulting number concentration is about 4% lower than in the two mode case, but the resulting mass concentration is about 42.6% larger than in the two mode case.

The referee recommended rejection of the paper, however, I would like you to consider this criticism - which cannot simply be dismissed - and respond to it. If these doubts can be dispelled, the manuscript would need to be revised in this regard, as it describes the merging of the two modes only quite superficially in the current version of the manuscript:
Lines 237 ff: '... once contrail ice and natural cloud ice occupy the same grid cell, their individual source contributions cannot be diagnosed explicitly; only the combined bulk response is represented.' An explanation is needed here regarding how the bulk response was combined and that this approach is microphysically sound.

The reason I am not following the reviewer's recommendation directly is that I think the base numbers for contrails might be adjusted. You write that
'Contrails are initialized under the assumption that they have already entered the post-vortex phase, approximately 450 s after formation, when atmospheric conditions dominate their development... '
The question is, how large are the contrail ice crystals at this stage? The 2.3µm assumed by the referee seems small to me. I recommend to estimate the size of the ice particles in the post-vortex phase, repeat the referee's exercise and check if it is consistent with your combined bulk response. For estimating contrail particle sizes there is literature available, e.g. Schröder et al. (200), JAS; Voigt et al. (2017), BAMS, Li et al. (2023), ACP.

I think the article will be further improved once this point is clarified. On the other hand, if the referee's assessment proves correct, two ice modes should be implemented in the model. It will then be decided how to proceed with this manuscript in this case.

Best wishes, Martina

…...

Martina Krämer
Senior Editor 'Clouds & Precipitation', Atmospheric Chemistry and Physics
https://www.atmospheric-chemistry-and-physics.net/editorial_board.html
Johannes Gutenberg-University Mainz - Institute for Physiks of the Atmosphere, Germany

Review of second revised version

Investigating the Development of Persistent Contrails in Ice Supersaturated Regions with Cloudy Backgrounds Using ICON-LEM

by Sajedeh Marjani et al.

General comment

It seems that my major concerns to this manuscript are not taken into account seriously. Actually, the major problem is here that the methods (i.e. the used model) are not appropriate for the respective inestigation. However, the authors refuse to make some addition model development, argueing that this kind of investigation have been carried out in a similar way recently, investigating contrails and cirrus clouds completely mixed up, and that this issue is not relevant for their study. Especially, I am missing some physical quantitative arguments, i.e. some calculations showing that the approach is meaningful or the errors are small or whatever.

I really disagree to the statement that the model is appropriate, and I give here one simple but crucial example based on back of the envelope calculations, which shows that the assumptions for using the model are not appropriate for this study. Actually, process rates of a fully mixed (contrails and cirrus) configuration are very different to the ones in the two mode case; thus, it is not clear at all if and how the results about contrails embedded into cirrus clouds are contaminated by this shortcoming or actual bias. There is a need for sorting out this issue.

Therefore, I would still recommend to reject the manuscript, the final decision rests with the editor.

Major issues

1. Contrails and natural cirrus clouds

   We know that especially shortly after the vortex phase, the microphysical characteristics of fresh contrails is very different to the cloudy environment. As shown by measurements (see, e.g., Schöder et al., 2000), the fresh contrail is a very narrow peak in terms of a size distribution, centered at about $1 - 5\,\mu\text{m}$, number concentrations are in the order of few per cubic centimetre. On the other hand, natural cirrus clouds have larger crystals (sizes up to hundreds of micrometres) in broader size distributions, and number concentrations in the order of few tens to hundreds per litre. Thus, the two species are very distinct. I would agree that for natural clouds one has such a high variability that one has to take into account a mixture of sizes, leading to a broad distribution. This is also not correct, however it is not possible to distinguish because of any different processes taking place at different times etc. . **However,** for the contrail vs. cirrus we know their very different characteristics very well, so we have to distinguish them for a better representation.

   I present here a very simple calculation, showing that without distinguishing between contrails and cirrus microphysical process rates are completely different, leading to other time evolution than in case of separate classes of ice. Such kind of calculations are needed for estimating the usefulness of a certain model configuration.

   We assume just spherical ice particles for simplicity, i.e.

   $$m = \frac{4}{3}\pi\rho_b r^3, \rho_b = 0.92 \times 10^3\,\text{kg}\,\text{m}^{-3} \tag{1}$$

   and for simplicity, the terminal velocity is proportional to the squared radius, i.e. roughly

   $$v_t(r) = a \cdot r^2, a \sim 10^8\,\text{m}^{-1}\text{s}^{-1}, \tag{2}$$

   assuming a relationship as represented by Lamb & Verlinde (2010).

We assume two different monodisperse ice modes:

(a) Contrails: $n_1 = 1000\,\mathrm{L}^{-1}, m_1 = 5 \times 10^{-14}\,\mathrm{kg}$, translating into a mean radius $r_1 = 2.3\,\mathrm{\mu m}$, and a total mass concentration $q_1 = 5 \times 10^{-8}\,\mathrm{kg\,m^{-3}}$. The terminal velocity can be estimated as $v_1 \sim 0.05\,\mathrm{cm\,s^{-1}}$.

(b) Natural cirrus: $n_2 = 100\,\mathrm{L}^{-1}, m_2 = 10^{-10}\,\mathrm{kg}$, translating into a mean radius $r_2 = 29.6\,\mathrm{\mu m}$, and a total mass concentration $q_2 = 1 \times 10^{-5}\,\mathrm{kg\,m^{-3}}$. The terminal velocity can be estimated as $v_2 \sim 8.76\,\mathrm{cm\,s^{-1}}$

If we just mix these ice crystals up and calculate the mean mass (as it is done in the model simulations, we get:

$$n = n_1 + n_2 = 1100\,\mathrm{L}^{-1}, \quad m = \frac{n_1 m_1 + n_2 m_2}{n_1 + n_2} = 9.14 \times 10^{-12}\,\mathrm{kg}, \quad r = 13.33\,\mathrm{\mu m} \tag{3}$$

The total mass is certainly the same $q = q_1 + q_2 = 1.005 \times 10^{-5}\,\mathrm{kg\,m^{-3}}$, but it is distributed with a peak at r (another monodisperse distribution by definition). The terminal velocity can be estimated as $v \sim 1.78\,\mathrm{cm\,s^{-1}}$, which is much closer to the value of the contrail ice crystals than to the natural ice crystals.

We investigate two different processes, i.e. diffusional growth and sedimentation; for estimating the effect of sedimentation, we further assume a vertical layer of thickness $\Delta z = 150\,\mathrm{m}$ (similar to the vertical model resolution) and a time interval of $\Delta t = 600\,\mathrm{s}$.

Actually, one can easily see from the simple calculations what might go wrong if one **does not distinguish** between these very different modes

(a) Diffusional growth: For spherical particles the growth equation for the total mass concentration is given by

$$\frac{\mathrm{d}q}{\mathrm{d}t} = nD(S_i - 1)r = n\tilde{D}(S_i - 1)m^{\frac{1}{3}} \tag{4}$$

for a certain saturation ratio S_i and a diffusion constant D depending on temperature and pressure, respectively. For a simpler comparison, we omit the constants and just set $\frac{\mathrm{d}q}{\mathrm{d}t} \sim nm^{\frac{1}{3}}$. If we now calculate the mass rates for (i) the two different classes, and (ii) for the mixed approach we obtain:

i. $\frac{\mathrm{d}q_1}{\mathrm{d}t} \sim n_1 m_1^{\frac{1}{3}} \sim 36.84$, $\frac{\mathrm{d}q_2}{\mathrm{d}t} \sim n_2 m_2^{\frac{1}{3}} \sim 46.42$, i.e. $\frac{\mathrm{d}q}{\mathrm{d}t} = \frac{\mathrm{d}q_1}{\mathrm{d}t} + \frac{\mathrm{d}q_2}{\mathrm{d}t} \sim 83.26$

ii. $\frac{\mathrm{d}q}{\mathrm{d}t} \sim nm^{\frac{1}{3}} \sim 229.96$

thus, the mixed growth rate is about a factor 2.76 larger than for the two mode case. This would lead to a very different time evolution, reducing the supersaturation much faster than in the first case.

(b) Sedimentation: If we approximate the sedimentation expression

$$\frac{\partial \phi}{\partial t} = \frac{1}{\rho}\frac{\partial(\rho\phi v_t)}{\partial z} \tag{5}$$

with a finite difference approach, we obtain

$$\frac{\partial \phi}{\partial t} = -\phi\frac{v_t}{\Delta z} \tag{6}$$

resulting into the solution $\phi(t) = \phi_0 \exp\left(-\frac{v_t}{\Delta z}t\right)$ for a quantity $\phi = n, q$. Thus, after a time interval Δt, the resulting number concentration is approximately[1] given by $n(\Delta t) = n_0\left(1 - v_t\frac{\Delta t}{\Delta z}\right)$ with $n_0 = n(0)$, and if we assume constant mass during sedimentation, we can simply calculate the resulting total mass concentration by $q(\Delta t) = n(\Delta t)m$. We obtain the following results:

- For two modes of ice we get
  $n_1(\Delta t) = 997.791\,\mathrm{L}^{-1}, q_1\Delta t) = 4.989 \times 10^{-8}\,\mathrm{kg\,m^{-3}}$ and
  $n_2(\Delta t) = 64.940\,\mathrm{L}^{-1}, q_2\Delta t) = 6.494 \times 10^{-6}\,\mathrm{kg\,m^{-3}}$, with a total number/mass concentration $n_1(\Delta t) + n_2(\Delta t) = 1062.731\,\mathrm{L}^{-1}$ and $q_1(\Delta t) + q_2(\Delta t) = 6.544 \times 10^{-6}\,\mathrm{kg\,m^{-3}}$.
  We loose only a few contrail ice crystals but a lot of the cirrus cloud crystals.

[1] we approximate the exponential function $\exp(-x) \sim 1 - x$

- For the mixed mode we get
  $n(\Delta t) = 1021.768\,\mathrm{L}^{-1}, q(\Delta t) = 9.335 \times 10^{-6}\,\mathrm{kg\,m}^{-3}$

  Thus, for the mixed mode the resulting number concentration is about 4% lower than in the two mode case, but the resulting mass concentration is about 42.6% larger than in the two mode case.

  Here, one clearly see that even the small differences in the terminal velocities result into huge issues. This is a well-known feature that in such schemes the falling ice is completely slowed down.

These examples of two basic processes should be enough to show that using a single ice class for contrails and cirrus in the same way as for natural cirrus clouds one introduces (well-known!!) biases, thus the results of contrails embedded into cirrus clouds might be affected crucially.

When I asked for some physical arguments for showing that the model is useful (or not) in the first review, this kind of argumentation (or similar ones) would have been appropriate.

2. Nucleation formulation for natural cirrus clouds

   In the model the formation of natural cirrus clouds by homogeneous nucleation is carried out using the scheme by Kärcher et al. (2006), which was designed for large time steps. As mentioned in the previous round of reviews, I think it is not appropriate to use this approach for high time resolution simulation (time step of 2 seconds). Since there is an adapted scheme (Köhler & Seifert, 2015) available, it is not understanable why the authors refuse to use this scheme. Since contrails are investigated within the natural environment, thus it would be necessary to represent natural ice clouds in a meaningful way, too.

   Again, I am convinced that this model configuration is not appropriate for investigating the scenario of contrails embedded into natural cirrus clouds.