Responses to the reviewers

Importance of aerosols and shape of the cloud droplet size distribution for convective clouds and precipitation

by C. Barthlott, A. Zarboo, T. Matsunobu, and C. Keil December 7, 2021

We thank both reviewers for reading the revised manuscript again. We have carefully considered all remaining comments of Reviewer 1 and changed the manuscript accordingly. Please find below our responses in blue.

Reviewer 1

The paper is certainly improved over the original submission, but I do have several additional comments.

Main comment:

1. Lines 237-240: But the sensitivity is not small for all strong forcing cases, only the one for which the heaviest precipitation occurs early. Perhaps a better way to ask my original question is, would you see the same negligible sensitivity in the red strong forcing case and any of the weak forcing cases if the red forcing case were started at say 18Z and if the weak forcing cases were started at say 10Z? Or, would you see increased sensitivity for the yellow strong forcing case if that simulations were started 12 hours earlier? In other words, is the sensitivity mostly a result of natural model spread that results from small changes in the pre-storm environment, or is it really that the CCN/shape parameter are having their biggest impacts during the precipitation events? If the latter, then I'd imagine that the sensitivity would not be especially sensitive to the model start time.

   We did not mention that the sensitivity in all strong forcing cases is small, we specifically mentioned the case of 2 June 2016 only:

   "The comparably small spread in precipitation intensities for both the CCN and shape parameter runs during the nighttime precipitation maximum on 2 June 2016 could be explained by the fact that particularly in cases with strong synoptic forcing, clouds act more like a buffered system and the response of precipitation to these microphysical uncertainties remains small."

   Two of the three strong forcing cases reveal a weaker sensitivity throughout the entire simulation time (13 September 2013 and 2 June 2016), such a behaviour was also found in previous work studying aerosol–cloud interactions with the COSMO model. The case of 11 June 2019, however, shows a strong sensitivity during the time of the precipitation maximum in the afternoon/evening. The stronger sensitivity cannot be attributed to the fact that precipitation intensities are high, because the case of 2 June 2016 reveals similar high rain intensities in the early morning hours. However, the sensitivity to CCNs or the shape parameter is small in that time frame. We therefore followed the reviewer's idea to relate the sensitivity to the model initialization time. However, we must state that it is not ideal to start the model at the time of a precipitation event or shortly before due to spin-up effects. We conducted all 8 model runs for 11 June 2019, but with an initial time of 18 UTC. The resulting sensitivity of the precipitation rates is given in Fig. R.1. It can be seen that the sensitivity is smaller as in the runs initialized at 00 UTC. We therefore believe that major precipitation events simulated in the first hours of integration are less affected by our microphysical perturbations as do runs with longer lead times.

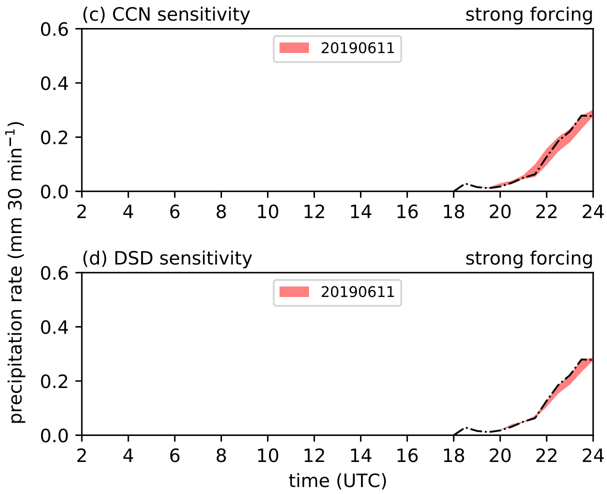

Figure R.1: Domain-averaged precipitation rates for the strong forcing of 11 June 2019 for a model initialization at 1800 UTC. The color-coded areas indicate the range between the minimum and maximum precipitation rate for all CCN sensitivities in (c) and all shape parameter sensitivities in (d). The black lines indicate the respective reference run with continental CCN concentration and a shape parameter of 0.

We modified the text in the manuscript as follows:

"The comparably small spread in precipitation intensities for both the CCN and shape parameter runs during the nighttime precipitation maximum on 2 June 2016 could be explained by the fact that ~~particularly in cases with strong synoptic forcing, clouds act more like a buffered system and the response of precipitation to these microphysical uncertainties remains small.~~ this maximum occurs during the first hours of simulation. In that time, spin-up effects and the adjustment to the driving coarser-scale model are still in effect, which could dampen the impacts of the microphysical uncertainties assessed here. A similar smaller impact of microphysics perturbations at short lead times was found in further sensitivity experiments for 11 June 2019 initializing the model at 18:00 UTC (not shown)."

We therefore hypothesize that although two out of three strong forcing cases generally reveal a weaker sensitivity, the short lead time for the nighttime precipitation maximum could buffer potential aerosol or shape parameter impacts for that case. We hope that this is sufficient and leave a more systematic evaluation of this effect to future work.

Minor comments:

2. Lines 64-80: Thanks to the authors for including this discussion. The authors may want to combine equations (3) and (4) since (4) follows from (3). As written, it is not obvious that this is the case, rather, the equations seem to be mysteriously equivalent. A reader familiar with distributions will know that $N0$ is equal to A in line 77, and that $a = 0.124$ m kg^{-b} arises from $(\pi/6\rho)^{-1/3}$, which is the factor appearing in multiple terms in line 77. But as is, the relationship between (3) and (4) is rather obscured by the use of different notations. I'd recommend making this discussion more transparent.

   We included the equations (2)–(4) in the revised manuscript as the reviewer requested a distinction between size distributions as a function of particle mass x and diameter D. Especially the approach in Eq. (2) may not be known to a reader unfamiliar with size distributions. But as Eqs. (3) and (4) seem to be confusing, we have again deleted Eqs. (2) and (3). Now, we only refer to the equations given in Khain et al. (2015) and hope that the use of one notation is sufficient.

3. I want to make the point again that if a typical range of f(D) shape parameters is 0-14 (Line 84), that this corresponds to a typical range of $f(x)$ shape parameters of -2 to 4 (using the conversion equation in line 77). The authors largest choice of $f(x)$ shape parameter, 8, corresponds to a f(D) shape parameter of 26, which is arguably unrealistic. I don't think anything major in the paper needs to be changed, but I think the authors should discuss the realism of their range. It may be helpful to explicitly include the converted range that I've mentioned here.

   We agree with the reviewer that our shape parameter values based on $f(x)$ should be converted for $f(D)$ for better comparison to literature values based on $f(D)$ as well. Therefore, we expanded Tab. 1 with ν'. A shape parameter value of $\nu' = 26$ might not be realistic and too large compared to observational values (0–14). The reason for letting ν' have such a wide range is to show how large the response of simulated clouds and precipitation could be in such extreme conditions. Furthermore, there is another cloud particle class often used in ICON with a shape parameter of 1 and a dispersion parameter of 1. The resulting CDSD looks broadly similar to the one with $\nu = 8$ and $\mu = 1/3$ (Fig. R.2), differences are mainly obvious for small droplet sizes.

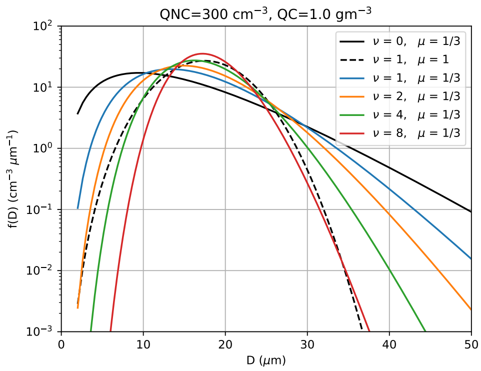

Figure R.2: Example cloud droplet size distributions.

4. Lines 163-166: Thanks also for this list of processes that are impacted by the shape parameter. However, previously the authors stated that they are using a saturation adjustment scheme, so the cloud droplet shape parameter and DSD properties can't possibly have an impact on condensation rates (and also evaporation rates?) in the model. Please can the authors review this list carefully?

   Thanks for pointing that out, the reviewer is right about the fact that the condensation rates are not directly influenced by the shape of the cloud droplet size distribution. In the course of the model run, however, we do see differences between condensation rates resulting from microphysical impacts on the thermodynamic environment. Evaporation is definitely influenced by the shape of the size distribution. We therefore deleted condensation from our list of processes.

5. I believe the microphysics scheme being used in this study is mostly the same as that described by Seifert and Beheng (2006), but I can't find that explicitly mentioned anywhere in the paper. Can the authors please provide a general reference for the scheme, if appropriate?

   Yes, we use the double-moment scheme of Seifert and Beheng. Maybe the reviewer missed it, it was already mentioned in the model description part (section 2.1 on page 5):

"For the simulation of aerosol effects on mixed-phase clouds, we use the double-moment microphysics scheme of Seifert and Beheng (2006a) which enables the use of four different CCN concentration assumptions."

6. Eq (5): I should have asked this the first time. Can the authors provide the expression used to calculate the effective radius in terms of the distribution parameters introduced in the introduction? I think this would help readers to explicitly see how effective radius is modulated by the shape parameter.

   In section 3.6, we mention the equation we use to compute the effective radius:

   $$r_{\text{eff}} = \frac{\int r^3 n(r)\mathrm{d}r}{\int r^2 n(r)\mathrm{d}r},$$

   where r is the droplet radius and $n(r)$ the cloud droplet size distribution. As we integrate the size distribution over the droplet radius, we believe that the influence of the shape parameter is understandable to the reader. The method to actually calculate the size distribution is given in Seifert and Beheng (2006a):

   $$f(x) = Ax^{\nu} \exp(-\lambda x^{\mu})$$

   The coefficients A and λ can be expressed by the number (N) and mass (L) densities:

   $$A = \frac{\mu N}{\Gamma(\frac{\nu+1}{\mu})}\lambda^{\frac{\nu+1}{\mu}} \text{ and } \lambda = \left[\frac{\Gamma(\frac{\nu+1}{\mu})}{\Gamma(\frac{\nu+2}{\mu})}\overline{x}\right]^{-\mu}$$
   $$\overline{x} = \frac{L}{N} \text{ mean particle mass}$$
   $$f(x) = \frac{N}{\overline{x}}\left[\frac{x}{\overline{x}}\right]^{\nu} \frac{\mu}{\Gamma\left(\frac{\nu+1}{\mu}\right)} \left[\frac{\Gamma\left(\frac{\nu+2}{\mu}\right)}{\Gamma\left(\frac{\nu+1}{\mu}\right)}\right]^{\nu+1} \times \exp\left\{-\left[\frac{\Gamma\left(\frac{\nu+2}{\mu}\right)}{\Gamma\left(\frac{\nu+1}{\mu}\right)}\frac{x}{\overline{x}}\right]^{\mu}\right\}$$

   Using a power law for the diameter-mass relation $D(x) = ax^b$ ($a = 0.124$ m kg^{-b}, $b = 1/3$), we can transform the equation from mass x to particle diameter D (or radius r):

   $$\begin{aligned} f(D) &= f(x)/(dD/dx) \quad D = ax^b \quad dD/dx = bax^{(b-1)} \\ &= f(x)/bax^{(b-1)} \end{aligned}$$

   We included a reference to the equations in the Seifert and Beheng paper and hope that this additional information is sufficient.

Reviewer 2

I have read the reply to my review and I think the authors did a very good job with answering my comments. I agree with their answers and I think the manuscript can be published in its current form.

We thank the reviewer for evaluating our reply to his comments.

Additional corrections:

- We changed the cloud albedo A to A_c because A was already used in Eq. 1 for the cloud droplet size distribution.