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 September 29, 2021

We thank both reviewers for reading the manuscript and providing detailed comments. We have carefully considered all comments and changed the manuscript accordingly. Please find below our responses in blue.

Reviewer 2

This paper studies the response of convective cloud systems and their precipitation production to changes in CCN and CDSD size distributions (concentration and shape parameter). Using the ICON model, numerical simulations of different synoptic systems (6 real cases) are conducted for the area covering central Europe. Comparison of the clouds and precipitation properties under different CCN size distributions is done for concluding about aerosol effects on deep convective systems. The simulated results, which are classified to weak and strong synoptic forcing, point on increased total cloud water and decreased total surface rain, with increased CCN concentration and narrower size distribution. The precipitation response is stronger for weakly forced cases. Explanations for these results are suggested by analysis of different hydrometeors types in the simulations and the related formation mechanisms. Less efficient collision-coalescence is demonstrated in more polluted cases (suppressed warm rain formation) and stronger rain evaporation at low levels. The simulated results also show a negative effect of aerosol on the convective intensity meaning there is no convective invigoration. This work examines the interaction of the clouds with their thermodynamic environment as well showing the impact of precipitation on the environmental instability. To summarize, it is a very interesting and valuable work dealing with an important subject which is still not fully understood.
We thank the reviewer for this positive comment.

I have a few comments that should be addressed before publication:

1. This study used a bulk microphysical scheme with a saturation adjustment assumption. This method is limited in its ability to simulate rightly the aerosol effect on warm cloud processes. First, the condensation efficiency cannot be accurately described by a saturation adjustment scheme. It was shown that the supersaturation values in clouds depend heavily on the aerosol loading (Pinsky et al., 2013, Seiki and Nakajima, 2014, Dagan et al., 2015). This major effect is neglected in this work. Another major effect is the aerosol impact on the drops' effective terminal velocity (Koren et al., 2015). A bulk scheme is limited in its ability to describe the full range of terminal velocities and so it neglects this major effect too. The authors should regard this major issue and the limitations of the method used here for this type of study should be discussed in more details.
   We agree with the reviewer that an explicit formulation of supersaturation might be beneficial. However, this option is not available in the ICON model. As stated by Seifert and Beheng (2006), all clouds, except extremely maritime ones, relax rapidly to the thermodynamic equilibrium between water vapor and water drops. Thus, applying the standard saturation adjustment technique to treat condensational growth seems to be appropriate in almost all cases. Moreover, many other models used for investigating aerosol-cloud interactions also use a saturation adjustment, e. g. COSMO_ART, ICON_ART or WRF (e.g. the Morrison scheme). Stensrud (2009) surveys that all single-moment bulk microphysical schemes and most double-moment

bulk schemes use bulk condensation, i.e. saturation adjustment instead of saturation prediction. There are a number of studies in the literature where the same microphysics scheme with saturation adjustment has been successfully used for investigating aerosol-cloud interactions, e.g.:

Noppel, H., U. Blahak, A. Seifert, and K. D. Beheng, 2010: Simulations of a hailstorm and the impact of CCN using an advanced two-moment cloud microphysical scheme. Atmos. Res., 96, 286–301.

Seifert, A., C. Köhler, and K. Beheng, 2012: Aerosol-cloud-precipitation effects over Germany as simulated by a convective-scale numerical weather prediction model. Atmos. Chem. Phys., 12, 709–725.

Rieger, D., Steiner, A., Bachmann, V., Gasch, P., Foerstner, J., Deetz, K., Vogel, B., and Vogel, H.: Impact of the 4 April 2014 Saharan dust outbreak on the photovoltaic power generation in Germany, Atmos. Chem. Phys., 17, 13391-13415, https://doi.org/10.5194/acp-17-13391-2017, 2017.

Barthlott, C. and Hoose, C.: Aerosol effects on clouds and precipitation over central Europe in different weather regimes, J. Atmos. Sci., 75, 42474264, https://doi.org/10.1175/JAS-D-18-0110.1, 2018.

Keil, C., Baur, F., Bachmann, K., Rasp, S., Schneider, L., and Barthlott, C.: Relative contribution of soil moisture, boundary-layer and microphysical perturbations on convective predictability in different weather regimes, Q. J. R. Meteorol. Soc., 145, 31023115, https://doi.org/10.1002/qj.3607, 2019.

Costa-Surs, M. et al.: Detection and attribution of aerosolcloud interactions in large-domain large-eddy simulations with the ICOsahedral Non-hydrostatic model, Atmos. Chem. Phys., 20, 56575678, https://doi.org/10.5194/acp-20-5657-2020, 2020.

Stensrud, D. J., 2009: Parameterization schemes: keys to understanding numerical weather prediction models. Cambridge University Press.

However, recent findings by Lebo et al. (2012) and Grabowski and Morrison (2017) suggest that the use of saturation adjustment has indeed implications for cloud development and surface rain amounts. The use of a saturation adjustment in the study of Lebo et al. (2012) enhances condensation and latent heating at lower levels and limits the potential for an CCN increase to increase buoyancy at mid to upper levels which leads to a small weakening of the convective mass flux in polluted compared to clean conditions. Grabowski and Morrison (2017) assumed clean conditions only and showed that the saturation adjustment produced more cloud buoyancy and stronger updrafts. They also state that the impact on surface precipitation is minor and subsequent studies using models with different representations of cloud microphysics and simulating clouds in different environments are needed.

Lebo, Z. J., H. Morrison, and J. H. Seinfeld, 2012: Are simulated aerosol-induced effects on deep convective clouds strongly dependent on saturation adjustment? Atmos. Chem. Phys., 12 (20), 9941–9964, doi:10.5194/acp-12-9941-2012.

Grabowski, W. W., and H. Morrison, 2017: Modeling condensation in deep convection. J. Atmos. Sci., 74 (7), 2247–2267, doi:10.1175/JAS-D-16-0255.1.

We included these comments in section 2.1:
"However, this technique has been shown to affect cloud development and rainfall through enhanced latent heating at lower levels (Lebo et al., 2012; Grabowski and Morrison, 2017) which

could reduce the potential for a CCN increase to increase buoyancy at mid to upper levels (Barthlott and Hoose, 2018). According to Grabowski and Morrison (2017), the impact on surface rain amounts was minor only.

...

Other recent studies on aerosol–cloud interactions with the ICON model also make use of the saturation adjustment technique (e.g. Seifert et al., 2012, Rieger et al., 2015; Heinze et al., 2017; Costa-Suros et al., 2020, Rybka et al., 2021)."

Regarding the terminal velocities:
In the double-moment scheme used in ICON, sedimentation is considered using the corresponding number and mass weighted mean fall velocities. The individual terminal fall velocities are calculated using an empirical relation similar to Rogers et al. (1993), but including an increase of the terminal fall velocity with height (Seifert and Beheng, 2006a). An exponential size distribution for the raindrop ensemble is used and the equation for the individual fall velocity is then integrated to get the weighted fall velocity. We believe that this technique is suitable for our purposes, as the terminal velocity does vary with the size distribution and self-collection or accretion is simulated in a meaningful way.

We added this text in the model description:
"Sedimentation is considered using the corresponding number and mass weighted mean fall velocities with the terminal velocity depending on the mean drop diameter (Seifert and Beheng, 2006a)."

2. This study examines the effects of changes in CCN and CDSD size distributions on deep convective systems. It examines both warm and cold processes. Nevertheless, there is no description or treatment of changes in IN size distribution. If there are changes in aerosol properties it will affect the IN properties and hence the mixed and cold processes. This issue should be explained in the manuscript regarding the treatment of IN in the model and its consequences on the results.
   We missed to include this information and now added these sentences in the model description section:

   "Heterogeneous ice nucleation in the immersion and deposition nucleation modes is calculated based on mineral dust concentrations described in Hande et al. (2015), whereas homogeneous ice nucleation is treated following Kärcher and Lohmann (2002) and Kärcher et al. (2006). The number of ice nucleating particles is not varied in this study, as we solely focus on the impact of different CCN concentrations and CDSD shape parameters."

   Thus, the differences in the cold rain processes presented in this study are a result of different warm rain processes, which affect (amongst others) the availability of water vapor, the amount of super-cooled liquid water, and the freezing of cloud and rain droplets.

3. The terminology used in the paper for describing the aerosol loading is very confusing (maritime, continental, polluted). The use of maritime and continental can regard the thermodynamic conditions as well and that why it is confusing. I suggest to change it to clean, intermediate, polluted and highly polluted and to use it in a consistent way throughout the paper.
   The terminology originates from the Seifert-Beheng double-moment scheme and has also been used in earlier papers using the same scheme (e.g. Keil et al. 2019, Schneider et al. 2019, Barthlott and Hoose 2018). In order to be consistent with those papers, we like to keep our terminology in that way. However, the reviewer is right about the fact that is not used consistently in the paper and sometimes we write "clean" instead of "maritime". We therefore replaced "clean" with "maritime" throughout the entire manuscript and rephrased the introduction to make it clearer:

"In addition, different aerosol amounts ranging from low CCN concentrations (representing maritime conditions) to very high CCN concentrations (representing continental polluted conditions) are assessed."

The wording "clean environment" and "clean air" was not changed.

4. In order to validate the model simulations there is a need to compare it to measurements. I suggest to add a figure which is similar to fig. 4 that will present observed accumulated rain or some other cloud properties for the 6 cases. This will enable estimation of the validity of the simulated results.

   A systematic model validation is not within the scope of the present study, because we solely focus on the sensitivity of the model to different CCN concentrations and shape parameters. Although the use of double-moment scheme has been shown to improve quantitative precipitation forecasting in some studies, the German Weather Service still uses a single-moment scheme due to computational costs. However, we agree with the reviewer that our simulations must reproduce the observed weather characteristics at least in a qualitative way. Therefore we compared the simulated 24-h precipitation of our reference runs to observations from a radar network combined with surface stations (RADOLAN, Radar Online Adjustment). It combines weather radar data with hourly surface precipitation observations of about 1300 automated rain gauges to get quality-controlled, high-resolution (1 km) quantitative precipitation estimations. The simulated precipitation of the reference runs generally show good agreement with observations (Fig. R.1) and the weather patterns of the days analysed are captured reasonably well. Even if not all precipitation is simulated at the right place with the correct intensity, we believe that these runs serve as a good basis for our analysis, as the focus of this study is the model sensitivity and not a quantitative evaluation or model improvement.

   We added this text at the end of section 2.2:
   "The intercomparison of the simulated precipitation amounts to Radar-derived precipitation (not shown) reveals that although the exact location of individual convective cells are not always simulated, there is an overall good agreement between observations and simulations. As the model succeeds reasonably well in reproducing the observed weather characteristics, we conclude that these reference runs serve as a good basis for our sensitivity studies."

5. Fig. 6: The meaning of the shading is not explained in the figure caption so the figure is unclear. It should be added.

   Thank you for pointing that out, we added the required information in the caption text.

6. The idea of considering the interaction of the convective clouds and the available instability as a type of "lifetime effect" is problematic as it treats a whole cloud system and not a single cloud (as the lifetime effect). This idea should be examined again and any way it should be explained better.

   The cloud lifetime effect was initially formulated for one particular cloud regime and the graphical illustration of this effect (e.g. Fig. 1 in Stevens and Feingold (2009)) indicates a single cloud as a representation of the average response of a field of clouds. We therefore believe that the lifetime effect is not restricted to one single cloud. However, we agree with the reviewer that our idea might be misunderstood by the reader and therefore removed the respective sentences in section 3.2 and the Summary. We replaced it with this formulation in Section 3.1:
   "As this interaction has an impact on the lifecycle of the convective clouds through decay and intensification, the entire lifetime of the cloud field is also affected, which highlights the complex interactions between thermodynamic and microphysical processes."

   Stevens, B., Feingold, G. Untangling aerosol effects on clouds and precipitation in a buffered

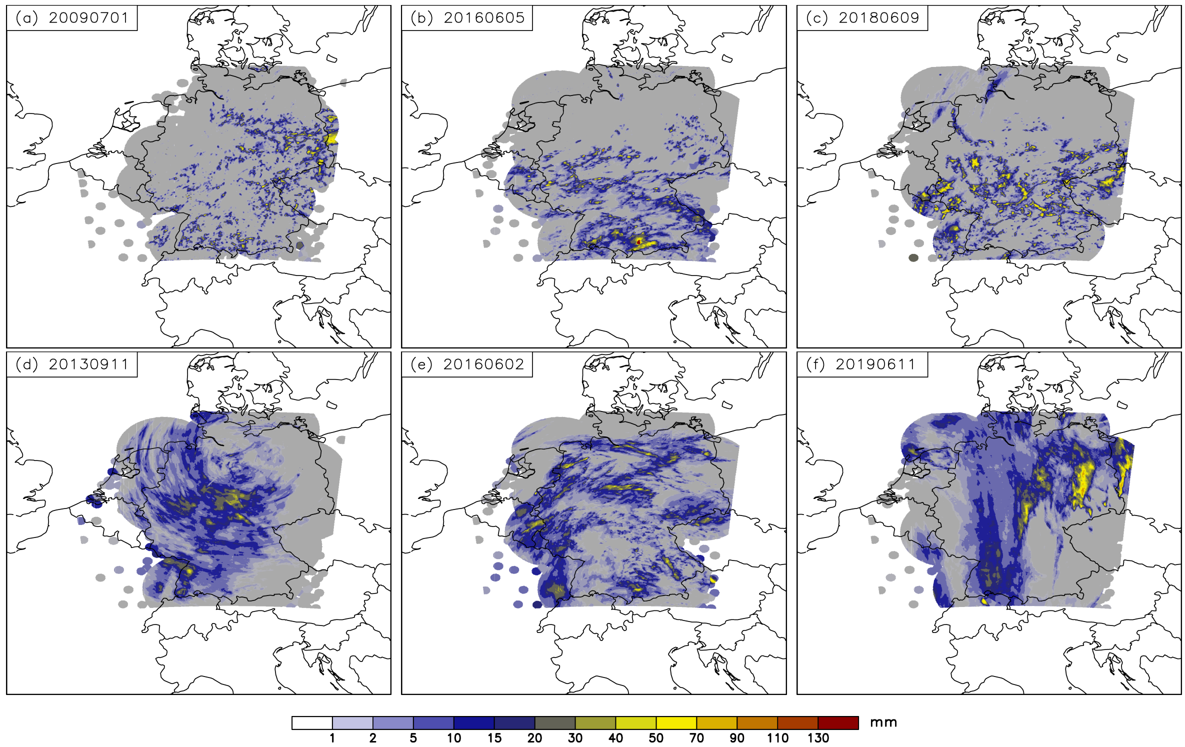

Figure R.1: Radar-derived 24-h precipitation amount from RADOLAN (Radar Online Adjustment).

system. Nature 461, 607613 (2009). https://doi.org/10.1038/nature08281

7. Fig. 8: I suggest to present mean vertical profiles of the different types of hydrometeors and cloud processes instead of the way it is presented now in figure 8 (similarly to fig. 7). The suggested way of presentation will connect better to fig. 7 and will help to present a full picture of the explanations.
   We agree with the reviewer that showing mean vertical profiles could be beneficial as also the height in which changes occur can be identified. However, we decided not to include such profiles due to these two reasons: First, our main interest is in displaying the total differences in a condensed way for all cases. If eight curves are displayed in one sub-figure (4 CCNs and 4 DSDs), it is sometimes hard to identify the total differences. Secondly, replacing Fig. 8 with mean profiles would mean to insert six figures for the cases analyzed in this paper which would blow up the manuscript unnecessarily. We therefore decided to keep Fig. 8 in its old form, but present one example of mean vertical profiles for a strongly forced case in our reply (Fig. R.2). For example, the systematic behaviour of melting is hardly visible in a vertical profile, whereas the differences of vertically integrated melting reveals a systematic increase to +20% for narrower cloud droplet size distributions in Fig. 8 of the manuscript.

The relevant papers:

1. Pinsky, M., Mazin, I., Korolev, A., and Khain, A. (2013): Supersaturation and diffusional droplet growth in liquid clouds, J. Atmos. Sci., 70, 27782793.

2. Seiki, T. and Nakajima, T. (2014): Aerosol effects of the condensation process on a convective cloud simulation, J. Atmos. Sci., 71, 833 853.

3. Koren I., Altaratz O. and Dagan G. (2015): Aerosol effect on the mobility of cloud droplets. Environmental Research Letters. 10, 10, 104011.

4. Dagan G., Koren I. & Altaratz O. (2015): Competition between core and periphery-based pro-

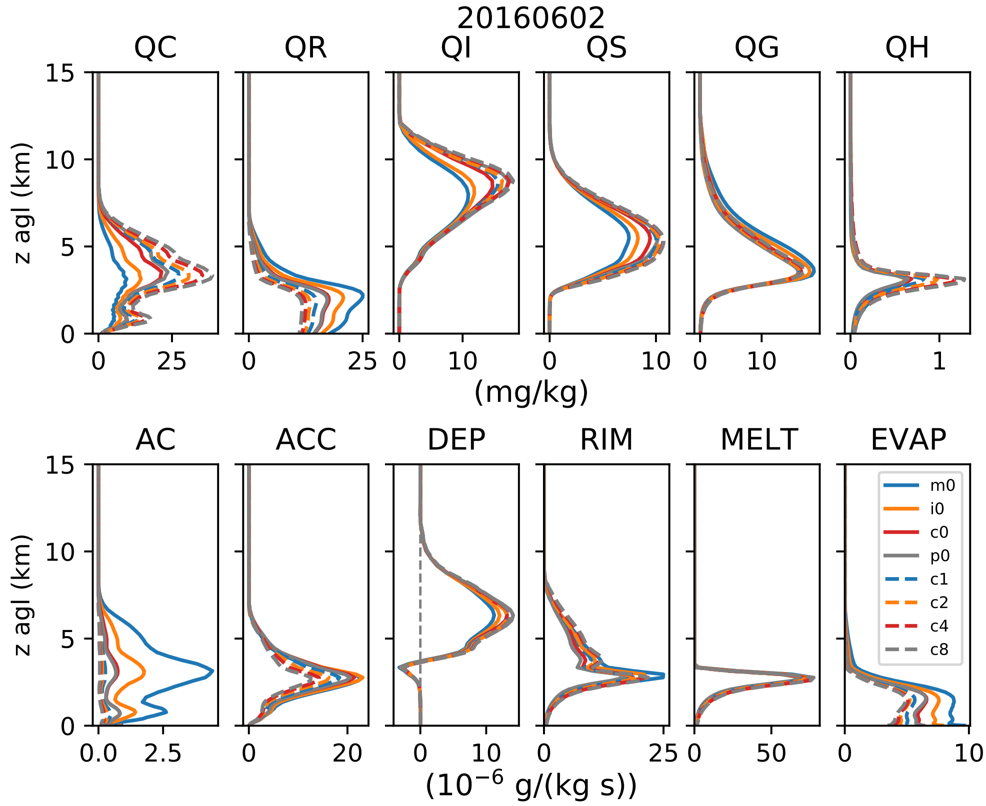

Figure R.2: Spatio-temporal averages of cloud water (QC), rain water (QR), ice (QI), snow (QS), graupel (QG), and hail (QH) amounts (top) and of autoconversion (AC), accretion (ACC), deposition (DEP), riming (RIM), melting (MELT), and evaporation (EVAP, bottom) for 2 June 2016.

cesses in warm convective clouds - from invigoration to suppression. Atmospheric Chemistry and Physics. 15, 5, p. 2749-2760