Responses to the reviewers

Impacts of combined microphysical and land-surface uncertainties on convective clouds and precipitation

by C. Barthlott, A. Zarboo, T. Matsunobu, and C. Keil August 1, 2022

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 study investigated the model uncertainties associated with three factors: soil moisture, CCN concentration, and the shape factor of cloud drop size distribution. Quite a few similar studies have been conducted recently, but none applied such a three- parameter combination. The results showed significant spreads caused by the two microphysical parameters, and the soil moisture factor also enhances the spread. But the significance of these factors compared to many others in the model is unclear. The manuscript can be enriched if the suggestions in the major comments below can be considered.

Note: I have posted a preliminary version of the review, and sorry for double-posting some of the comments.

Major comments

Introduction and methodology:

1. As the authors stated, model uncertainties exist in many physical schemes and dynamics, including initial/boundary conditions (IC/BCs). There can be numerous combinations of such uncertainty sources. Can the authors explain why it is essential to consider the combination of soil moisture and cloud microphysics compared to other possible combinations?
   Soil moisture influences the initiation and development of convective systems and many papers in recent years documented the complex land-surface precipitation relationship, e.g. the review article of Liu et al. (2022). Although the influence of soil moisture on convective precipitation follows some definite rules, the relationship is complex and the direction of the soil moisture influence on convective systems and precipitation can vary. As soil moisture controls the partitioning of the available energy at the ground into sensible and latent heat, the structure of the planetary boundary-layer is significanty affected. This is not only important for convection initiation, but also for already existing convective systems which depend upon the existence of CAPE. In the operational data assimilation system of the German Weather Service (DWD), soil moisture is also one of the disturbed parameters. On the other hand, microphysical uncertainties are not yet included operationally, but are shown to have a non-negligible impact in this work and also in a prior study (Barthlott et al., ACP, 2022). We do not state that the combination of soil moisture and microphysical uncertainties are essential to consider or superior to other ways of generating an ensemble, but we believe that the spread of the results of our method looks promising and that the comparison with other sources of uncertainty should be done. First efforts in this direction have been performed by Matsunobu et al. (WCD, 2022). As soil moisture and microphysical uncertainties both influence cloud development at different stages and their individual impact has been demonstrated in many recent papers (Schneider et al. 2019; Keil et al. 2019), we believe that our method of combined uncertainties is well suited to be compared to other sources of uncertainty.

We added this statement in the introduction:
"We choose these uncertainties because (i) their individual impact was documented in many recent studies and (ii) all have an impact on the life cycle of convection at different stages from its initiation to the decay."

2. Similarly, there are many uncertainties in cloud microphysical parameterizations. How are these factors considered in this study? Can the authors justify why they focused only on uncertainties in NCN and CDSD parameters? Also, the authors mentioned many uncertainties related to aerosol-cloud interactions (lines 45-76). Can these uncertainties be represented by perturbing the NCN?
We agree with the reviewer that there are many uncertainties in cloud microphysical parameterizations. However, it was not the goal of this study to investigate many different microphysical uncertainties as our concept of combined uncertainties based on soil moisture, CCN concentration, and shape parameter already yields to an ensemble size of 60. Moreover, as the analysis of microphysical process rates shows, many different processes are affected directly and indirectly. We therefore believe that our uncertainties affect many microphysical pathways although only warm-rain processes are influenced directly. Including more microphysical uncertainties is out of the scope of the present study. We included a reference to Wellmann et al. (2020) who investigated more microphysical uncertainties, but only for idealized simulations. We added this sentence at the end of section 2.1:
"The reference run would therefore be labeled as run REFc0. Including more microphysical uncertainties (e.g. ice nucleating particle concentration, hydrometeor sedimentation, or ice multiplication) as in idealized simulations by Wellmann et al. (2020) could be considered in the future, but were not performed at the moment due to the high number of possible combinations."

3. Line 122-123: There is a difference between NCN and NCCN (CN stands for condensation nuclei and CCN for cloud condensation nuclei). For polluted continental conditions, the value of 3200 cm-3 seems to be too low for NCN (should be tens of thousands or more) but fine for NCCN. The values used for other conditions should also be justified or, at least, provide a reference.
Thanks for pointing that out, we corrected the text, it now reads:
"Pre-calculated activation ratios stored in look-up tables (Segal and Khain, 2006) are used to compute the activation of CCN from aerosol particles. The condensation nuclei are all assumed to be soluble and follow a bi-model size distribution (Seifert et al., 2012). Using the Segal and Khain (2006) activation, four different values of the number density of CNN (N_{CCN}) are available, representing maritime (N_{CCN} = 100 cm^{-3}), intermediate (N_{CCN} = 500 cm^{-3}), continental (N_{CCN} = 1700 cm^{-3}), and continental polluted conditions (N_{CCN} = 3200 cm^{-3}). Typical conditions of central Europe are represented by the continental aerosol assumption (Hande et al., 2016)."

4. The shape parameter ν is also important for other hydrometeors. In fact, the variation in ν may be even more prominent for precipitation particles according to some triple-moment schemes. What is the reason for perturbing only ν of cloud drops?
As already mentioned above, not all microphysical uncertainties can be assessed in our study. One reason for taking the shape parameter of the CDSD was the fact that it is not well constrained by observations and many different values exist in the literature. The results of our study also shows the indirect effect on rain and ice formation via the large differences in microphysical process rates. Also the already quite high number of possible perturbations when using the three uncertainties analyzed here inhibits us from considering even more uncertainties at the moment.

Results:

1. The model "spread" is one of the key foci of this study. Yet, the discussion on the normalized standard deviation (indicating the spread) is too brief and does not provide much scientific insight.
   Please see our reply to the next point.

2. I would like to see a more quantitative comparison of spreads from the three sensitivity factors (i.e., soil moisture, CCN, and shape factor. This allows the reader to judge which factors are more important for the consideration of ensemble members.
   As suggested by the reviewer we performed such a separate analysis of the three impact factors and included the temporal evolution for all days in new Figure 7. The time series of the total ensemble spread is based on 60 members whereas for the individual contributions, the ensemble size is smaller. E.g. for the soil moisture sensitivity, there are only 3 members with identical CCN and shape parameters. The ensemble spread was then averaged over all 20 3-member ensembles. Thus we applied bootstrapping to randomly pick 3 suitable combinations and repeated that procedure 100 times. Due to the smaller size of the sub-ensembles, the individual contribution from CCN, shape parameter, and soil moisture may not be fully reliable because the normalised spread is actually bounded by the square root of ensemble size and all spreads become very similar when ensemble size is very small. The important point is the total spread of the 60-member ensemble (black lines in new Fig. 7) which lies in a similar range as an operational ensemble for a high-impact weather period in 2016. Furthermore, we believe that the model spread is also visible in the deviations of accumulated precipitation (Fig. 5) and the precipitation rates (Fig. 6).

   We included the new Figure 7 together with this text:

   " Beside an ensemble spread based on all 60 members, we also computed the spread induced by soil moisture, CCN, and the shape parameter individually. As only three soil moisture regimes are available for each identical CCN concentration and shape parameter, we used the bootstrapping method to randomly pick between different suitable combinations to calculate their normalised spread. This procedure was repeated 100 times. The results show that the area-averaged local precipitation variability introduced by varied CCN concentrations and shape parameters is rather similar (Fig. 7). This finding holds true for all days irrespective of the synoptic-scale forcing. For both uncertainties, the variability increases rapidly already in the first hours of the forecast, followed by a rather constant plateau until a further increase occurs in the afternoon at the peak of convective activity (see rain rates in Fig. 6). In contrast to that, the variability due to soil moisture reveals a weaker increase early in the simulation and reaches similar high values (or even higher ones on 9 June 2018) as CCN and shape parameter variability only around noon. In the afternoon, a similar weak increase is simulated as in the other types of uncertainty. Later, soil moisture variability remains slightly below the ones from CCN and shape parameter. For a high-impact weather period of 2016, Keil et al. (2019) found that the spread induced by soil moisture was slightly larger than the one induced from different CCN concentrations in the afternoon. However, in their study soil moisture was perturbed by applying high-, low- and bandpass filters to introduce surface perturbations which is different from our approach of using a soil moisture bias. Figure 7 further reveals that..."

3. Line 249-250: "The higher the CCN concentration, the lower are the rain intensities." This seems to be a warm-rain characteristic. But, apparently, the studied systems are mostly cold-rain dominant (lines 443-444). For mixed-phase convective systems, higher aerosol concentrations often lead to stronger rain intensity (cf. Tao et al. 2012, etc.). It will be nice to compare the results

here with other relevant studies.
The results of our study are based on mixed-phase convective systems, but the cold-rain contribution is always dominant, at least when integrated over the entire day. The previous work of Barthlott et al. (ACP, 2022) documented dominant warm-rain contributions only for very weak rain intensities probably at very early stages of the precipitation formation in clouds. There are a number of studies who also find a precipitation reduction with increasing CCN concentrations and we mentioned at least some of these in the manuscript in the introduction:

"However, the impact of aerosols on convective precipitation has been shown to differ between cloud types, the aerosol regime, and environmental conditions (e. g. Seifert and Beheng, 2006b; Khain et al., 2008; van den Heever et al., 2011; Tao et al., 2012; Barthlott et al., 2017)."

We added this text in section 3.1 discussing the decreasing precipitation totals with increasing CCN:

"The validity of the convection invigoration mechanism proposed in Rosenfeld et al. (2008) is still open and many studies documented a decrease of total precipitation with increasing aerosol concentrations (e.g. Tao et al., 2012; Storer and van den Heever, 2013). Using idealized simulations, Grant and van den Heever (2015) showed that the influence of aerosols varies inversely with storm organization and Fan et al. (2009) found that vertical wind shear qualitatively determines whether aerosols suppress or enhance convective strength. "

4. Figure 7. The tendency of TQG change with ν is different for maritime CN compared to other CN types for cases 2018 and 2020. Some inconsistencies also exist in the 2016 case. Is there any explanation?
We mentioned in the manuscript that the case with systematic graupel reduction with increasing CCN or shape parameter is the one with the highest integrated graupel content (10 June 2019), the remaining cases had much lower graupel contents. A closer look at the microphysical process rates reveals that the response of graupel follows mostly the one from graupel/hail riming with cloud droplets (Fig. R.1). We also see that riming with cloud droplets is dominating the riming with rain droplets. For maritime CCN conditions, there is no large sensitivity to the shape parameter, but for polluted conditions and already narrow CDSD, the impact is higher for the three cases with lower overall graupel contents .

We added this remark in the manuscript:

"Some of the cases show decrease in graupel mass for maritime CCN conditions and an increase for higher CCN concentrations. This can be attributed to graupel/hail riming with cloud droplets which increases with larger shape parameters for already more narrow size distributions (not shown)."

Conclusion:

1. It is dangerous to make a conclusion based on only four cases. Large differences can be observed between the two weak cases or between the strong cases, which may suggest that other cases may behave distinctively differently and even produce results that disagree with the conclusions stated here. Furthermore, the uncertainties in the studied parameters may vary if you choose different initial/boundary conditions, physics schemes, or grid resolutions. The authors should at least try to tone down a bit on the certainty of their findings.
We are aware of the fact that general conclusions cannot be based on 4 cases only. Altogether, we constructed our 60-member ensemble for 8 cases but only mentioned 4 of them in the text. We made this selection because the sensitivity was mostly similar among the cases and the detailed analyses of the microphysical processes for every day would only lengthen the manuscript

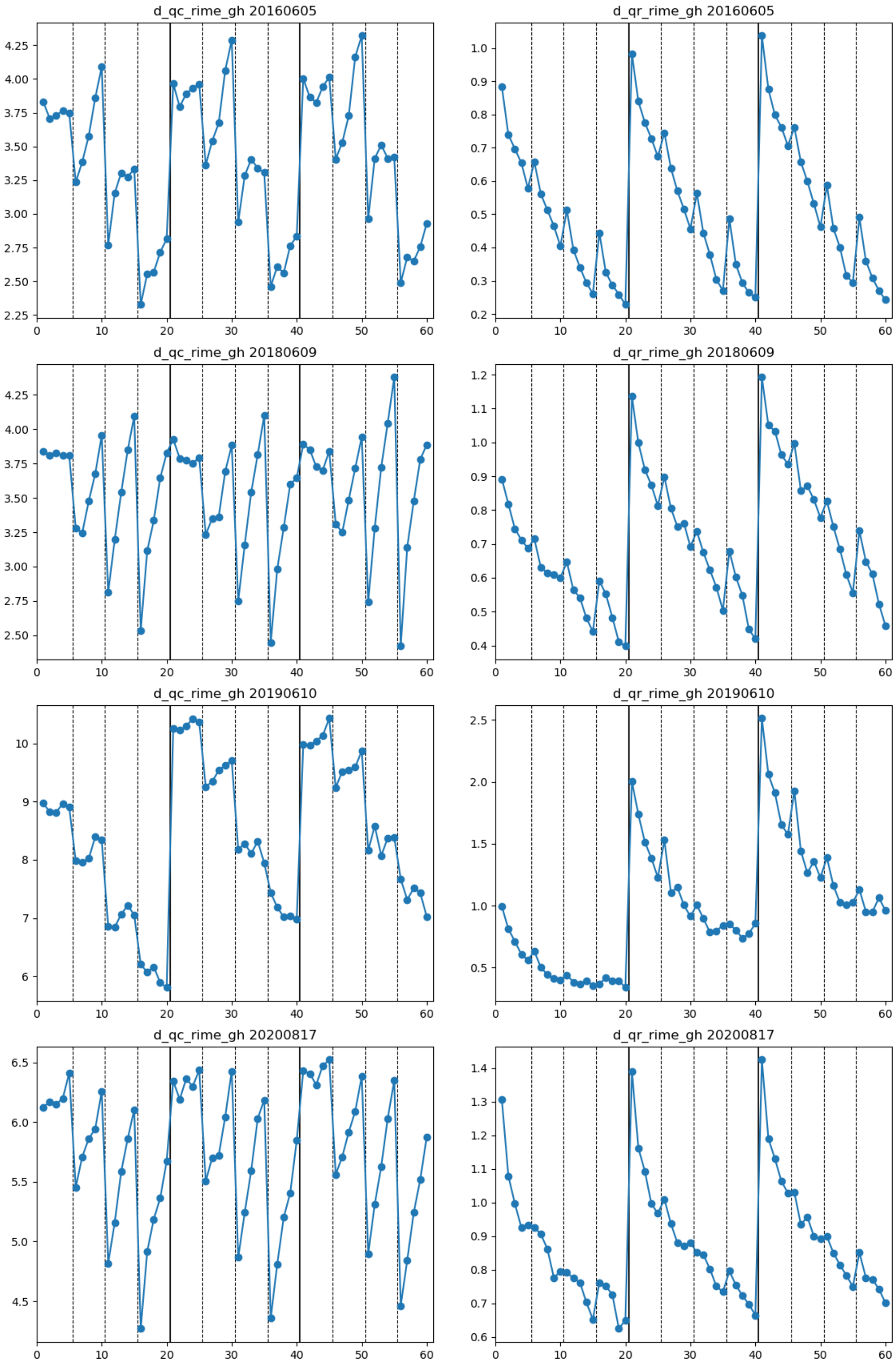

Figure R.1: Spatiotemporal averages of graupel/hail riming with cloud droplets (left) and with rain droplets (right) from the respective reference run in kg/(kg 24 h).

unnecessarily.

2. Perhaps the authors can make a quantitative comparison of the spread caused by each factor by preparing a table summarizing the relative spreads (standard deviation).
   We now included such a quantitative comparison, please see our reply to comment Results no. 2.

3. There are quite a few similar studies with multiple-factors analyses. Because of the numerous possible combinations of uncertainty factors, it will be nice to see some comparisons on the spread/uncertainty with previous studies.
   We included a couple of new citations in the introduction:

   "Other studies with multiple-factor analyses exist mostly for idealized setups, e.g. for investigating the impact of environmental conditions and microphysics on the forecast uncertainty of deep convective clouds and hail using an emulator approach by Wellmann et al. (2020), for investigating aerosol–cloud–land surface interaction within tropical sea breeze convection (Grant and Heever, 2014) or investigating the relative sensitivity of a tropical deep convective storm to changes in environmental and cloud microphysical parameters (Posselt et al., 2019). Using the Morris one-at-a-time (MOAT) method for simultaneous perturbations of numerous parameters, Morales et al. (2019) explored the sensitivity of orographic precipitation within an environment of an atmospheric river. "

   and these sentences in the Conclusions:

   "To our knowledge, only Grant and Heever (2014) and Baur et al. (2022) studied synergistic effects of aerosols and soil moisture so far. Grant and Heever (2014) conducted idealized cloud-resolving simulations of tropical sea breeze convection and found precipitation reductions by over 40% and 50% for the most extreme perturbations. The realistic convection-resolving simulations of Baur et al. (2022) were conducted for a single case study only, but they found a similar sensitivity of precipitation deviations as in this study (-23% and +10%)."

Minor comments

1. Line 5: 60 member ensemble → 60-member ensemble (same in other places of the text)
   done

2. Line 12-13: rain water → rainwater
   We would like to keep the spelling as it is, since it was written the same way in a previous companion study in ACP:

   Importance of aerosols and shape of the cloud droplet size distribution for convective clouds and precipitation by Christian Barthlott, Amirmahdi Zarboo, Takumi Matsunobu, and Christian Keil, Atmos. Chem. Phys., 22, 2153–2172, https://doi.org/10.5194/acp-22-2153-2022, 2022

3. Line 14: strong, but → strong but
   done

4. Line 14: non systematic → non-systematic
   done

5. Line 15: which → , which
   done

6. Equation (1): Since the microphysics scheme used is double moments with A and λ as varying coefficients, ν and μ must be specified. The value for μ was never mentioned. If μ was set to 1,

then just omit it in the equation.
We added this sentence in the manuscript:

"The dispersion parameter is kept constant in all simulations ($\mu = 1/3$)."

7. Figures 5, 7-9: These figures are quite complicated. More details (e.g., what is NU) are needed in the caption to assist the readers in understanding the arrangements.
   We are aware of the fact that these figures are complicated and already tried to give as much information in the caption as possible. Although the shape parameter is mentioned there, NU was not. We now included that and hope that the reader has now all necessary information. The caption of new Figs. 8–11 now contain information that the arrangement of the data points is exactly as in Figure 5.

8. Line 215: applies for → applies to
   done

Preliminary version of review:

As the authors stated, model uncertainties exist in many physical schemes and dynamics, including initial/boundary conditions (IC/BCs). There can be numerous combinations of such uncertainty sources. Can the authors explain why it is essential to consider the combination of soil moisture and cloud microphysics compared to other possible combinations?
Please see our reply to major comment 1 above.

A similar question: there are many uncertainties in cloud microphysical parameterizations. How are these factors considered in this study? Can the authors justify why they focused only on uncertainties in N_CCN and CDSD parameters? Also, the authors mentioned many uncertainties related to aerosol-cloud interactions (lines 45-76). Can these uncertainties be represented by perturbing the N_CCN?
Please see our reply to major comment 2 above.

The discussion on the normalized standard deviation is too brief and does not provide much scientific insight.
Please see our reply to Results comment 1 and 2 above.

I would like to see a more quantitative comparison of spreads from the three sensitivity factors (i.e., soil moisture, CCN, and shape factor.
Please see our reply to Results comment 1 and 2 above.

Additional corrections

We re-phrased some of the text in order to remove passages which had similarities to previous work. The meaning of the sentences was not changed, therefore the changes are not highlighted in the tracked-changes version.