

We would like to thank all three reviewers for their constructive criticism of our manuscript. Their comments have helped us to improve the text.

Point-by-point replies are inserted below. The reviewers' comments are in italics, while our answers are in normal font. Where we refer to new/modified text from the manuscript, this is given in blue color.

Anonymous Referee #1

This study examines the relative influence of environmental conditions and microphysical parameters on vertically integrated hydrometeor contents and precipitation values (with an emphasis on hail), in addition to their influence on heating rates. The authors use an emulator technique to reduce the number of simulations that would otherwise be required to produce the presented results. In general, the study finds that environmental conditions and microphysical properties contribute to forecast uncertainty; however, when the environment and microphysics interact with each other, the latter tends to dominate forecast uncertainty in hydrometeor contents and precipitation.

Overall, I have a long list of comments; most importantly, I think that the authors should provide more analysis and discussion in several of the sections (please see general and specific comments). The paper is well written, but readability could be improved by a more liberal use of commas in addition to the rewording of several sentences (please see specific comments). In addition, the authors should try to be consistent about their use of active versus passive voice. With all of this said, I think that the results are interesting and worthy of publication, and at this stage I suggest acceptance subject to major revision.

We thank the reviewer for the constructive comments. We have addressed all comments individually below. Additionally, we have improved the language in the entire manuscript.

Major/general comments:

1. Model Setup (Section 2) and Methods (Section 3): For clarity, and especially for those readers who are not familiar with the emulator technique, there should probably be more information included about the modeling approach.

For example, what is the total number of simulations conducted?

We have used $15 \times k$ input combinations to train the emulator, with k the number of input parameters, which is 6 in S1, 7 in S2 and 6 in S3. Furthermore, 10 simulations were added to the training datasets of S1 and S3 to increase the quality of the emulator fit. Thus, per Setup, 100 (S1 and S3) or 105 (S2) simulations were run to generate the training data. Additionally, 45 simulations with other input parameter combinations were conducted per setup for the evaluation of the emulators. In sum, the total number of simulations is 440.

This information has been added in section 3.1.

Which "input combinations" are simulated?

The explanation is given on p. 8: „This is ensured by the use of maximin Latin hypercube sampling (Morris and Mitchell, 1995) to select these input combinations.“ The combinations of input parameters used in the three setups have been added to the published dataset accompanying this study (doi:10.5445/IR/1000099232).

How does your choice for the mean function and correlation structure influence the results?

The choice of the linear trend for the mean function and the Matérn correlation structure have been discussed in more detail by Lee et al. (2011), and have since then be used by a number of studies (Johnson et al., 2015; Igel et al., 2018; Wellmann et al., 2018, Glassmeier et al., 2019). We have not investigated the impact of this choice in our study, and think that adding such an analysis would go beyond the scope of this manuscript. We have added these references to the text.

Glassmeier, F., Hoffmann, F., Johnson, J. S., Yamaguchi, T., Carslaw, K. S., and Feingold, G.: An emulator approach to stratocumulus susceptibility, *Atmos. Chem. Phys.*, 19, 10191–10203, <https://doi.org/10.5194/acp-19-10191-2019>, 2019.

Igel, A. L., Heever, S. C., & Johnson, J. S. (2018). Meteorological and land surface properties impacting sea breeze extent and aerosol distribution in a dry environment. *Journal of Geophysical Research: Atmospheres*, 123, 22–37. <https://doi.org/10.1002/2017JD027339>

Lee, L. A., Carslaw, K. S., Pringle, K. J., Mann, G. W., and Spracklen, D. V.: Emulation of a complex global aerosol model to quantify sensitivity to uncertain parameters, *Atmos. Chem. Phys.*, 11, 12253–12273, <https://doi.org/10.5194/acp-11-12253-2011>, 2011.

How do you validate the emulator?

As described in Wellmann et al. (2018), 45 additional simulations, also sampled via maximin Latin hypercube sampling, were conducted for the validation (per setup). When comparing the emulator results to the results of the validation simulations, only a small number of outliers (up to 3) outside the 95% confidence intervals are accepted. In addition, a test for robustness of the choice of the training dataset has been conducted by interchanging the training dataset with parts of the validation data. This information has been added to the text in section 3.1.

Are the emulator results sensitive to the chosen minimum and maximum parameter values?

Yes, the “Main effect” scales directly with the parameter range, so this selection is crucial for the interpretation of the results. This is now stated more clearly in the Summary & Conclusions (“[Note that the range of variation of these parameters is designed to mimic typical forecast errors and is therefore smaller than in earlier studies, which have encompassed a wider range of possible conditions.](#)” and “[For our choices of input parameter ranges, ...](#)”). In section 2, we have added the following sentence: “[Note that as the results depend crucially on the ranges over which the parameters are varied, these have to be chosen carefully and taken into account when comparing to other studies.](#)”

What is the argument for including CCN and INP in the environmental conditions setup?

CCN and INP concentrations are linked to aerosol concentration and type, which changes in different environments (e. g. urban compared to marine). This is different for the other microphysical parameters in S2, for which the variation spans a range of uncertainty due to e.g. different ice densities of graupel and hail, which are not clearly linked to specific conditions.

Do the results change notably if these two microphysical properties are included only in the microphysical conditions setup?

No, because the comparative evaluation is based on setup S3.

2. Sensitivity Analysis for Variations of the Microphysics (S2) (Section 4): This section, which represents the bulk of the paper, generally lacks depth and therefore should contain additional insight and discussion.

The aim of this study was not a detailed process analysis, but a general overview and a statistical quantification of the relevance of the uncertainty of various parameters. The large ensemble is not well suited for the investigation of causal relationships. Nevertheless, we have inserted more discussion on possible explanations for our results, partially based on related studies.

For instance: [P9, L14-20] Why look at the mean for hydrometeor content, max for precipitation, and both for amount of hail?

The output variables have to be reduced to 0 dimensions in order to be represented by the emulators. This requires averaging or selecting the maximum values. Our reasoning was that, in general, we are

interested in the variables that are linked to severe weather at the surface (as precipitation maxima and hail), but also in the in-cloud processes causing them. For this, the mean hydrometeor loads are of interest. We have added this information to the text.

[P9, L31-32] *What about snow and hail as contributors to the output uncertainties? Maybe this should say one of the largest contributors.*

We have modified the sentence as follows: “Fig. 1 reveals that of the investigated parameters, the graupel fall velocity factor a_G is the largest contributor to the output uncertainties of most of the integrated hydrometeor masses”.

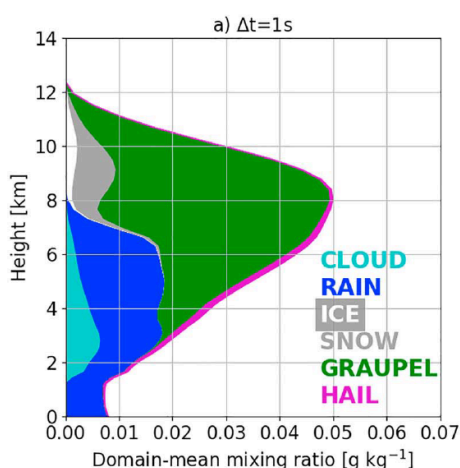
[P9, L39-40] *Total precipitation, which is a very important quantity, seems to be affected more notably by the fall speed of graupel scaling factor than by CCN. Please comment on this.*

This is likely due to cold phase processes (riming, depositional growth) dominating precipitation formation, as was shown e.g. by Schneider et al. (2019) for cases of strong convection. Riming is more directly impacted by the graupel fall velocity than by CCN, although the latter has an indirect impact via the modification of droplet size.

At the end of section 4.1, we have removed the sentence “Contributions from the other parameters are only of minor importance” and added the following new text: „For the maximum total precipitation, the scaling factor for the fall speed of graupel, a_G , is also relevant. This is in line with the expectation that for cases of strong convection, cold phase processes (including riming onto graupel) dominate precipitation formation, as was shown e.g. by Schneider et al. (2019)“.

3. Heating rates (Section 4.2): *The results from this section are quite interesting; however, I feel as though it is lacking a bit in terms of analysis and discussion. It would be nice if the authors took some time to dive a little deeper. For example: [P11, L17-18] Why is the fall speed of graupel the most important at low altitudes (<2 km) and high altitudes (>10 km), which is where the graupel heating rates are very small if not zero? Is graupel present in these regions? Perhaps a figure showing vertical profiles of hydrometeor contents may help.*

This is an interesting point. We have decided not to include additional figures with the vertical profiles of hydrometeor content to save space, because they are in line with the diabatic heating rates and do not offer surprises. Below we show the hydrometeor profiles from Fig. 3 of Barrett et al. (2019), who used a near-identical model setup. We have also added a reference to this figure in the text.



The contribution of CCN and graupel fall speed to uncertainty of the heating rate at $z > 12$ km can be explained as follows: In COSMO, graupel is not only produced by riming, but also by freezing of rain drops, and therefore many (actually rather small) graupel particles are present at altitudes up to 12 km. At the cloud top, the freezing occurs homogeneously and is not related to the INP concentration nor the scaling

factor introduced for INP. Therefore, the production and subsequent sublimation of ice hydrometeors at high altitudes is impacted by CCN (which impact how much rain water is produced and transported to the homogeneous freezing level), but only to a small extent by INP. The graupel fall speed impacts riming at lower levels in the cloud (again impacting how much rain water is transported to the homogeneous freezing level) and in addition determines the gravitational sink of the graupel particles present at these altitudes. Snow and ice contribute to a larger extent to the latent heating by sublimation at these altitudes, but the parameters determining their fall speeds have not been considered here.

We have added the following more concise explanation to the text: “Above [10 km], the output uncertainty of the total heating rate is dominated by the CCN concentration and the fall velocity of graupel. This is probably linked to the indirect effect of CCN and riming efficiency on the amount of supercooled water transported to the homogeneous freezing level. Furthermore, graupel is produced at these levels in our model as a result of the freezing of rain drops, and the graupel fall speed factor thus impacts the gravitational sink of the (small) graupel particles present at these altitudes.”

For the explanation of the graupel impact on heating rates at $z < 2$ km, we refer to the analysis of vertical profiles of hydrometeors and process rates in Barrett et al. (2019), who used a very similar configuration and base case setup of the COSMO model. At lower levels, rain evaporation (together with cloud water condensation) is the main term in the latent heating rain. As shown by Barrett et al. (2019), roughly 50% of the surface rain originates from cold rain processes involving riming. Therefore here the graupel (and also hail) fall speed parameters contribute substantially to the uncertainty of the latent heating rate at levels below 2 km, although there is no graupel present at these altitudes.

To include this into the text, we have added/reformulated the following sentences: “In the height between 3 km and 4 km there are also major contributions from the fall velocity of rain a_R . Below, coinciding with the largest cooling due to the evaporation of rain, a_G is again the major driver of uncertainty. As shown by Barrett et al. (2019), roughly half of the surface rain in this model setup originates from cold rain processes involving riming. Therefore here the graupel (and also hail) fall speed parameters contribute substantially to the uncertainty of the latent heating rate at levels below 2 km, although there is no graupel present at these altitudes.”

[P11, L18-19] Where the fall speed of rain plays a notable role in the main effect (between 3 and 4 km), the magnitude of the rain heating rate is only a small fraction of the magnitude of the total heating rate. Does this suggest that, in general, the model physics is more uncertain about rain evaporation processes than cloud condensation processes?

This is possibly linked to the saturation adjustment used for cloud condensation, which is thus insensitive to droplet number and size, while rain evaporation is treated as a time- and size-dependent process. We have added the following sentences: “CCN contributes only modestly to uncertainty at these levels, although the heating rate by condensation is very strong here. This is probably linked to the fact that a saturation adjustment scheme is used for cloud condensation, which is thus insensitive to droplet number and size.”

[P12, L2-3] Can you speculate as to why the CCN concentration and fall speed of graupel dominate the total heating rate output uncertainty at high altitudes?

As explained above, we think that this is an indirect effect. It is important to note that the parameters are not changed level by level, but for the entire setup; thus, changes in the graupel fall speed affect how much riming occurs in the lower levels of the cloud and thereby controls how much liquid water is transported to higher altitudes (and causes latent heating there by freezing or evaporation). Additionally, the graupel fall speed controls the gravitational sink of graupel at the cloud top. Similarly for the CCN concentration, which (among other things) impacts the efficiency of warm rain formation at lower levels and therefore the rain water content at the homogeneous freezing level.

4. Hydrometeor masses and precipitation (Section 5.1): In general, this section would benefit from a deeper (and more quantitative) analysis. Figure 4 is really nice for visual comparison; however, can the numerical values be put into a table (perhaps in an appendix or a supplement) for a more quantitative comparison?

Yes, the numerical values have been added as Tables A1 and A2 in the appendix.

Also, to minimize reader confusion, I recommend not putting a circle in areas where the input parameter was not part of the emulator simulation. For instance, under S2 for shear, under S1 for graupel fall speed, etc.

In a revised version of the figure, the circles for these input parameters have been removed.

Some comments and questions about the section text: [P14, L4-6] When referring to the trend for precipitation output, what about for total precipitation rate, which appears to be different? Is this important? Again, a table would help clarify these comparisons.

The reviewer is correct that the CCN contribution to the main effect is similar in S1 and S2, but smaller in S3 for the maximum total precipitation rate, while it decreases steadily from S1 to S2 to S3 for the maximum accumulated total precipitation. However, we don't think this effect should be overemphasized, because it could be due to the choice of showing the maximum and not the mean, such that there is some noise in the results.

[P15, L3] When referring to the main effect of the INP concentration, what is the physical interpretation? The influence of uncertainty in the INP concentration is muddled when the uncertainty in the other (individual? some? all?) microphysical parameters are introduced? Please elaborate.

We hypothesize that secondary ice formation can drown the effect of primary ice formation when it's very efficient. Similarly, when the graupel fall speed is large, this can result in very efficient riming and therefore consumption of supercooled liquid, again reducing the importance of heterogeneous ice nucleation. We have added these thoughts to the text:

"Thus, the main effect of the INP concentration is smaller if other microphysical parameters are used as input, possibly because other ice phase processes (secondary ice formation, riming) can suppress the sensitivity of a cloud to primary ice formation."

Minor/specific comments:

1. P1, L15-17: Maybe reword to make more clear that you are emphasizing environmental parameters and microphysical parameters. Also, please separate the citations to better associate with these two different aspects of forecasting convective clouds.

Rephrased to: *"Thus, numerous studies have been published on simulating deep convective clouds. These have investigated how environmental parameters like wind shear (e. g. Weisman and Klemp, 1984, Lee et al., 2008), and the aerosol environment, which determines the CCN concentration (e. g. Lee et al, 2008; Rosenfeld et al., 2008, Fan et al., 2013), affect the clouds in these simulations."*

2. P2, L3: What are the different choices of the trigger?

We have added this to the text: *"a warm bubble, a cold pool or a bell-shaped mountain ridge"*.

3. P2, L5-6: Please add references for the Morrison and Thompson schemes.

Done.

4. P2, L6-7: Which aspects of the parameterizations are most influential?

We have inserted this information by extending this sentence as follows: *"They find that the use of the two schemes causes larger differences than the changes in the number concentration, primarily because of the representation of autoconversion of cloud water to rain and of cloud ice to snow."*

5. P2, L8: Individual parameters such as?

This sentence was confusing and has been removed.

6. P4, L7: Horizontal resolution or grid spacing?

We meant grid spacing. This has been rephrased.

7. P4, L9: Can you provide approximate vertical grid spacings in the layer(s) of interest?

We have added this information to the text:

“These levels follow the transformation given in Gal-Chen and Somerville (1975) such that they are denser near the ground and further apart with increasing height (approximately 300 m vertical distance at 5 km altitude and 400 m vertical distance at 10 km altitude). Variables are written out and analysed on interpolated z-levels with 250m vertical distance up to 3km and 500m vertical distance above.”

8. P4, L9: Do the open boundary conditions cause any mass conservation issues?

The mass of the individual tracers in the domain is not conserved, because the considered air mass eventually leaves the domain. However, we have selected the domain size such that the cloud does not reach the domain boundaries within the considered simulation time.

We have added the following sentence to the text: “During this simulation period, the clouds do not reach the boundaries of the domain.”

9. P4, L20: How are cloudy grid boxes defined?

We have specified this more clearly now:

“We consider only cloudy grid points (where the vertically integrated content of any hydrometeor type is >0) in our analysis of the vertically integrated hydrometeor contents.”

10. P4, L26: Which “two former studies”?

We have replaced this part of the sentence by “... using only the key inputs of the setup with variation of environmental conditions and the new setup with variations in microphysical parameters, in order to enable a comparison of the relative importance of environmental and microphysical uncertainties for model output uncertainty.”

11. P5, Table 1: The fourth input says “potential temperature at the ground”, but the text says “vertical temperature profile”. Please clarify.

The Weisman & Klemp (1982) temperature profile follows the function

$$\theta(z) = \theta_0 + (\theta_{tr} - \theta_0) \left(\frac{z}{z_{tr}} \right)^{\frac{5}{4}} \quad \text{for } z \text{ below the tropopause height } z_{tr}, \text{ which has a fixed potential temperature } \theta_{tr}.$$

Thus, θ_0 is the potential temperature at the ground, but it impacts the entire tropospheric profile. We have modified the text by inserting “This variation of θ_0 impacts the entire tropospheric profile and corresponds to a change of CAPE ...”.

Furthermore, we have inserted Weisman & Klemp’s equation for the temperature profile.

12. P5, L6: Perhaps “maritime” should be changed to “clean” because marine cloud can be polluted.

Done.

13. P5, L17-18: This sentence is confusing...does it turn toward the west until a straight easterly flow is reached or does it turn toward the east until a straight westerly flow is reached?

We have added the equation for the profile of the wind direction to remove any ambiguities.

14. P5, L20: Please state explicitly the wind direction bounds at the surface.

As requested, we have added this information to the text:

“Here, we vary F_{shear} only between 0.3333 and 0.6666, corresponding to a wind direction at the ground between 210° and 240°, which reflects the typical error range of the operational COSMO forecast of the wind direction (Felix Fundel, personal communication, 2017).”

15. P5, L20: Please add a citation for this statement.

Unfortunately, there is no citable peer-reviewed document for this statement, but we have specified our source as “(Felix Fundel, personal communication, 2017)”.

16. P5, L23: Please add a citation for this statement.

Again, there is unfortunately no citable peer-reviewed document for this statement, but we have specified our source as “(Felix Fundel, personal communication, 2017)”.

17. Table 2: Please add the symbol/abbreviation for the various parameter inputs (where necessary).

We have added the variable names a_R , a_G and a_H in Table 2.

18. P7, L11: Why not also vary μ ?

We follow here Igel and van den Heever (2017a,b). With the dispersion parameter $\mu=1/3$, the general gamma distribution of Seifert and Beheng (2006a) for the cloud droplet mass reduces to a (simple) gamma distribution for the drop diameter, which is the type of distribution used by Igel and van den Heever (2017a,b). We have not been able to find any studies on the spread of the dispersion parameter in observations. An earlier study with the Seifert and Beheng (2006a) cloud scheme (Noppel et al., 2010) has also changed μ , but we think that this additional parameter would not add another dimension of uncertainty to our ensemble.

We have added a reference for Igel and van den Heever (2017a).

Igel, A.L. and S.C. van den Heever, 2017: The Importance of the Shape of Cloud Droplet Size Distributions in Shallow Cumulus Clouds. Part I: Bin Microphysics Simulations. J. Atmos. Sci., 74, 249–258, <https://doi.org/10.1175/JAS-D-15-0382.1>

19. P7, L32: Please change “data” to “output”.

“output” wouldn’t fit well here because at this point the model output is the input to the variance-based sensitivity analysis. Therefore we’d like to remain with the neutral term “data”.

20. P8, L20-21: Can you comment on the errors that are associated with this prediction?

In response to one of the major comments, we have added information on the validation of the emulator. This also answers the question about the possible error of the prediction:

“Once an emulator is constructed, it needs to be validated to ensure an accurate estimation of the model output (Basots and O’Hagan, 2009). For this, an additional 45 simulations with other input parameter combinations were conducted per setup. When comparing the emulator results to the results of the validation simulations, only a small number of outliers (up to 3) outside the 95% confidence intervals are accepted. In addition, a test for robustness of the choice of the training dataset has been conducted by interchanging the training dataset with parts of the validation data. The validated emulator is then able to predict (with a certain error as constrained by the validation) the output at all points in the multi-

dimensional parameter uncertainty space that were not included in the training set and thus replaces the costly simulations of the NWP model."

21. P9, L16: Contents or vertically integrated contents?

This sentence has been changed to "The spatial and temporal mean is taken for the considered vertically integrated hydrometeor contents."

22. Figure 2: Is it possible to coordinate the y-axes of the two panels so that a direct comparison in the vertical is easier?

This proved to be technically difficult because the main effect is diagnosed on more densely spaced levels below 3 km (250 m) than above (500 m). The bars would become unreadable in the lower levels if this was taken into account. Therefore we have kept the plot as it was, but have added a note of caution to the caption: "Note the different axis tick spacing below and above 3 km."

23. P11, L13-15: While this is true, perhaps note that the total heating rate does not decrease as rapidly as the rate due to cloud water because graupel and ice heating rates are at a maximum between about 8 and 10km.

The reviewer is correct. We have added more emphasis on the positive contributions from graupel and ice by changing the next sentence to "At higher altitudes, there are additional positive contributions from the formation of graupel and ice."

24. P12, L31-33: The impact of the fall speed of hail and the strength of ice multiplication is mentioned as being important, but what about the role of the fall speed of graupel? This seems quite important for small hail. Moreover, can you speculate as to why CCN concentration becomes more important at larger hail diameters?

In COSMO, hail can form through two different processes: riming of graupel and freezing of rain. This may explain the different sensitivities to CCN and a_G of different parts of the size distribution. However, a more detailed process analysis is not possible within our framework. We have added the following text:

"At the largest considered diameters, an increased contributions from the CCN concentration comes into play, while smaller diameters are significantly impacted by the graupel fall speed. This may be linked to the two formation pathways of hail in COSMO, namely through freezing of rain (of which the size is impacted by the CCN concentration) and through riming of graupel."

25. Table 3: What is the difference between assigning the input parameters "lower" and "higher" values as opposed to "min" and "max" values (as in Tables 1 and 2)? Also, why are the values used in this experiment different from those used for S1 and S2? Is the input listed as "potential temperature" at the surface?

There was an error in the parameter values for F_{shear} in Table 3. The correct values are 0.3333 and 0.6666, thus the same as in Table 1. This has been corrected.

As discussed in Wellmann et al. (2018) and in section 2.1, the parameter range for F_{shear} and θ_0 has been restricted to the amplitude of typical forecast errors. For the other parameters, we have tried to encompass all possible values when defining the model setups, but have restricted them to a narrower range of more likely values based on literature for the analysis of the hail size distribution. This choice is certainly, to some extent, subjective.

We have added the following text: "Hereby, the outer bounds of the environmental parameters F_{shear} and θ_0 from S1 are taken as "-" and "+", as they are already limited to the typical range of forecast errors. For all other parameters, the lower and higher values are subjectively chosen to be representative, but not extreme, and encompass therefore a smaller range than examined in S1, S2 and S3."

26. P14, L1 (below Fig. 4): Can you parenthetically reference the CCN and INP concentrations here to help the reader?

Done.

27. P15, L4-7: *Maybe note that, in general, uncertainties in wind shear (which is likely not uncommon in numerical weather prediction) do not have a notable impact on the output variables examined here with the exception of integrated rain water content (rain water path).*

As suggested, we have added this information and reformulated the relevant sentences:

“The behavior of the wind shear is quite consistent for the considered output variables. Its contribution is in general small, except if the integrated rain water content is the target output variable. It is always larger in S1 than in S3, meaning that the wind shear has a larger impact on the output uncertainty, if only the environmental conditions are varied.”

28. P15, L6: *Perhaps note that the impact of theta is already relatively low.*

As suggested, we have changed this sentence to: “Similarly, the (already small) impact of θ_0 ...”

29. P15, L31-32 (“The remaining input parameters [...]”): *I am not sure that I understand this sentence. Please clarify.*

This sentence has been changed to: “The other input parameters (ΔT , radius, a_R , the ice multiplication factor and the shape parameter) are only used in one of the setups so that a direct comparison of different setups is not possible.”

30. P15, L34-35 (“in particular from the fall velocity of graupel for the hydrometeor masses and from the fall velocity of hail for precipitation”): *This seems like an important finding; please italicize for emphasis.*

Rather than italicizing this statement, we now emphasize our findings further by iterating it in the abstract and the conclusions:

“The microphysical parameters, especially the fall velocities of graupel and hail, lead to larger uncertainties in the output of integrated hydrometeor masses and precipitation variables.”

“The study combining both sets of input parameters shows a large contribution by the fall velocity of graupel to the output uncertainty of the hydrometeor loads, and by the fall velocity of hail to the output uncertainty of the precipitation variables.”

31. P15, L35-36: *So, are you able to say that uncertainties in the selected environmental conditions are muddled by uncertainties in the selected microphysical parameters?*

Our point is here that it depends what one is looking at. For the diabatic heating rates, the uncertainties in environmental conditions dominate, but for the hydrometeor and precipitation variables, the uncertainties in microphysical variables prevail.

32. P15, L50-51 (“In their study [...]”): *This sentence is a bit confusing; please reword and/or flesh out.*

This paragraph has been reworded as follows:

The impact of CAPE on deep convection is analyzed by Storer et al. (2010). In their study, the updraft strength and the total accumulated precipitation are very sensitive to changes in CAPE, while the integrated amount of cloud water does not depend strongly on CAPE. Furthermore, they conclude that the impacts of CAPE and CCN concentration can be comparable.

33. P16, L7: *To which aerosol effect(s) are you referring?*

“aerosol effect” has been replaced by “impact of CCN variation”.

34. P16, L8-11: Can you be more specific about the Fan et al. (2013) results? Changes up to 25%? 25% on average? Is their range of CCN concentration similar to the one used here? Also, for the Yang et al. (2017) paper, what range of CCN concentration was tested? This is important when comparing previous results to results from the current study.

This paragraph has been revised to include more information on the parameter ranges and results of the cited studies.

“With respect to the impact of CCN variation, our findings are in qualitative agreement with the works of Fan et al. (2013) and Yang et al. (2017), for instance. Fan et al. (2013) find an increase of approximately 30% of the upper tropospheric cloud cover due to changes of the CCN concentration from 280 to 1680 cm^{-3} (which is smaller than our parameter range). Yang et al. (2017) find clear differences in the vertically integrated condensate mixing ratio, such as an increase of ice from 6 to 18 g kg^{-1} , for increasing CCN from 300 to 5000 cm^{-3} (similar to our parameter range). This is comparable to the significant influence of the CCN concentration on the output uncertainty of the hydrometeor contents found here.”

35. Figure 5: For the left panel, please mark the 0 K/h value to delineate between negative and positive values. Also, for both panels, is it possible to make the lines thicker in this figure (as in Fig. 2)?

We have marked the 0 K/h line and have made the lines thicker in the left panel. In the right panel, there is too much overlap among the different lines, such that the readability would be reduced if the lines were thicker.

36. P17, L17-18: When talking about the saturation adjustment in the microphysics scheme, how are you able to make this conclusion? Please elaborate.

We didn't mean that the saturation adjustment would cause the uncertainty, but wanted to iterate that the condensation is parameterized via a saturation adjustment scheme. To clarify this, these two sentences have been reformulated:

“Condensation of cloud water, which is a substantial contributor to the total heating rate in the lower and middle troposphere, is parameterized via a saturation adjustment scheme in our model. Nevertheless, it yields a large contribution to output uncertainty of the diabatic heating in all three setups. This effect might be even larger if a time-dependent treatment of condensation was used.”

37. P17, L33-34: When talking about the emulator-predicted size distributions, are you able to comment on the expected uncertainty in your results?

As discussed above (major comment #1 and minor comment #20), during the validation of the emulators it was required to meet the simulated values within the 95% confidence intervals.

38. Figure 6: As in Fig. 5, are you able to make the lines thicker?

The figure has been modified as suggested.

39. Size distribution of surface hail (Section 5.3): For the analysis in this section, please use line color and style to help clarify to which distribution you are referring.

As suggested, we have added “(continuous blue line)”, “(dashed blue line)” etc. to the text.

40. P18, L5: When referring to the value of 0.4 $\text{mm}^{-1} \text{m}^{-3}$, this number does not seem to correspond with the y-axis. Am I missing something here?

Thanks for pointing this out. There was a mistake in the text, while the figure was correct. This has been corrected.

41. P18, L7: Similar to comment #40, when referring to the value of $3.4 \text{ mm}^{-1} \text{ m}^{-3}$, this number does not seem to correspond with the y-axis.

See above.

42. P18, L7-9: This sentence is confusing. Perhaps say something like: "when relatively high (low) values of θ_0 and high (low) concentrations of CCN and INP are present, low (high) hail number concentrations result".

We wanted to stay closer to our original wording, but have modified this sentence as follows: "For this setup (in which the environmental conditions are modified), the controlling parameters are the CCN and INP concentrations and θ_0 . Low number concentrations of hail arise for higher values of these parameters and high number concentrations of hail for lower values."

43. P18, L10-12: This could probably be stated more simply in one sentence. For example, something like: "For S2, the maximum and minimum of the hail size distribution is larger and smaller than that for S1, leading to a larger spread in the distributions."

We have modified the sentence as follows:

"For S2, the low (dashed red line) and high (continuous red line) hail size distributions are smaller and larger, respectively, than those for S1, leading to a larger spread in the distributions."

44. P19, L3-10: What about for larger diameters? It is especially interesting that the number concentrations for the minimum size distributions are largest for S3. This suggests that, individually and for the lower bound, S1 and S2 do not produce large number concentrations, but if the environmental and microphysical conditions are combined (S3), then there is an enhancement. Please comment on this notable difference.

There are two factors which make us cautious not to overinterpret this result: (a) the hail size distribution was not a target parameter when selecting the subset of parameters from S1 and S2 to be included in S3. Thus, maybe the size distribution is more sensitive to parameters in S1 and S2 which were not considered in S3. (b) the shaded area, delimited by the dashed and continuous lines, is only based on 64 combinations of parameter values. Possibly one could find more extreme hail concentrations for other parameter combinations.

For these reasons, we prefer not to speculate on this feature of the plot in the manuscript.

45. P19, L8-10: So, can you speculate as to what this means physically?

This sentence was a mere semantic explanation. We have omitted it now and have instead specified:

"Moreover, the controlling parameters identified in S3 include parameters from both environmental conditions (INP) and microphysics (a_G , a_H)."

46. P19, L12-13 ("While the microphysical input parameters mainly determine the maximum number concentration, the environmental conditions substantially influence the minimum number concentration"): This seems like an important finding; please italicize for emphasis.

We think that this statement, which is also repeated in a similar form in the conclusions, is already emphasized enough.

47. P20, L17-27: There is a large body of literature, some of which is referenced in the introduction, that focuses on the so-called "aerosol invigoration" hypothesis. Can you relate the work presented here to previous work?

Note that while we find that CCN is a very important parameter for both hydrometeor load and precipitation, this does not yet give a sign of the dependence. Indeed, we have been able to find configurations in which CCN increases cloud water content as well as others in which it decreases cloud

water content. A further analysis with different target variables (e.g. cloud water content in different evolution stages of the cloud) would be interesting. However, we think that this discussion is out of the scope of this manuscript.

48. P21, L19-20: *What about also a revised parameterization of the fall speed of graupel?*

We have incorporated this suggestion and have changed the sentence to "... in particular a revised parameterization of the fall velocity of graupel and hail".

Grammatical/wording recommendations:

1. *The authors interchange hydrometeor "content" and "mass" throughout the text. Which parameter is actually shown? Please be consistent.*

To be precise, the "hydrometeor mass content" (in kg m^{-3}) was meant. We have changed the wording throughout the manuscript to either "mass content", or simply "content" where there is no ambiguity.

2. *P2, L4-5: Awkward sentence; please reword.*

Sentence changed to "In addition to thermodynamic profiles and environmental conditions determining the formation and structure of deep convective clouds, also microphysical parameterizations have been shown to play a role."

3. *P2, L5: Change "three cloud types for" to "three cloud types using".*

Done.

4. *P2, L19: Maybe "Additional relevant" instead of "Further relevant"?*

Done.

5. *P2, L28: Change "Moreover, field studies indicate that fall speeds of hydrometeors are observed in a broad range of velocities." to "Moreover, field study observations indicate that hydrometeors may have a broad range of fall velocities."*

Done.

6. *P2, L30-32: Awkward sentence; please reword.*

Changed to "Gilmore et al. (2004) and Posselt and Vukicevic (2010) vary both the fall speeds and the densities of hail/graupel and snow, and find that these parameters impact the amount of precipitation significantly."

7. *P3, L10-12: Awkward sentence; please reword.*

Done.

8. *P3, L12: No need for "different".*

We have changed as suggested to "wide range of ambient conditions".

9. *P3, L13: Change "sometimes thermodynamic conditions are the main drivers, sometimes dynamic conditions" to "either thermodynamic conditions or dynamic conditions may be the main driver".*

Sentence changed to "In reality, severe convective storms form in a wide range of ambient conditions, where either thermodynamic conditions or dynamic conditions may be the main driver, leading to different organizational forms of the storms."

10. P8, L31: "in the Fourier space along all parameters change simultaneously" is awkward; please reword.

We have removed "along [which] all parameters change simultaneously."

Anonymous Referee #2

General Summary: This well-written work explores the environmental and microphysical uncertainties that produce the largest variability in deep convection and hailfall characteristics. The authors make an excellent point that the impact of such uncertainties needs to be considered not only in isolation, as previous studies have largely done, but also in relationship. Hence, the work will be an excellent contribution to the literature. There are a few points about the effect of the chosen microphysical parameterization and comparison of variability to other studies that I would like clarified, but generally I support the acceptance of the article pending minor revisions.

Specific comments:

1. These results have to potential to be highly related to the choice of microphysical scheme, and as such, this impact needs to be discussed in the paper. How much of an effect do certain choices made in the microphysical scheme have on these results – for example, could the chosen hail/graupel ice collection efficiency relationships affect the high variability found to be associated with the ice multiplication coefficient? What about the density of the rimed ice? (Frankly, I was surprised that wasn't chosen as an input parameter to vary as multiple studies have noted its importance; e.g. Morrison et al. 2015, JAS.) Most importantly, are these results transferrable to other double-moment microphysical parameterizations with a similar number of classes, or are they unique to this scheme alone?

We have not repeated our study with a different microphysics scheme, but agree with the reviewer that a certain dependence on the parameterizations is to be expected. However, our main aim was not to emphasize the impact of a specific parameter, but rather to weigh the relevance of environmental versus microphysical uncertainty. We expect that this result is less dependent on the microphysics scheme.

We have added the following paragraph to the conclusions: “It can be expected that our results (in particular regarding the microphysical parameters) depend to some extent on the microphysics scheme of our model. However, the overarching aim of this study was not to emphasize the impact of a specific parameter, but to quantify the relevance of environmental versus microphysical uncertainty in general. We expect that these results are less dependent on the microphysics scheme.”

Considering the rimed ice density as a possible parameter, we expect that this effect would be closely linked to variation in the graupel and hail fall speed, which we have varied in our study.

2. The environmental condition input parameters (surface potential temperature and wind shear) are varied over a smaller range than most environmental sensitivity test studies. The authors explain this range of environmental conditions was chosen as it corresponds to typical environmental uncertainties seen in COSMO. Limiting the perturbation to that range is important, in my opinion, as it allows the work to make judgements about which model improvements are most likely to improve simulations of convection and hailfall. However, the results cannot be compared to other works examining the impact of the full range of environmental conditions that can produce hail, such as Dennis and Kumjian (2017) and Storer et al. (2010), without explicitly comparing the ranges of inputs of environmental conditions in all studies. I would like the article, especially the abstract, to emphasize that the input range of environmental conditions is only meant to encompass model uncertainty.

We agree with the reviewer that this is an important point and that our results cannot be directly compared to the mentioned studies. We have rephrased the last sentence of the abstract as follows: “In contrast, variations in the environmental parameters – the range of which is limited to represent model uncertainty – mainly affect the vertical profiles of the diabatic heating rates.”

Additionally, we have added a sentence in the Summary & Conclusions section: “First, a set describing environmental conditions such as potential temperature and vertical wind shear was used. Note that the range of variation of these parameters is designed to mimic typical forecast errors and is therefore smaller than in earlier studies, which have encompassed a wider range of possible conditions.”

To that end, more information about how the variations in surface potential temperature and the scaling factor for 0-6 km shear translate to typically cited ambient environment conditions, such as CAPE and 0-6 km

shear, would be helpful. The shear in particular is important given the results of Dennis and Kumjian (2017). A hodograph plot showing the range over which the shear profile was varied would be useful.

We have now inserted the equations for the profile of the wind direction and the potential temperature. In addition, we give the bounding values for CAPE and for the wind direction at the ground. (The wind direction at 6 km is 270° in all simulations.) We have decided not to include plots of the hodographs in order to limit the number of figures.

3. I'd like more information about the emulators, inputs, and training data. Pg. 8 line 6 mentions using a "choice of input combinations of the parameters" to train the emulator. What combinators are selected and how is the choice made? How many simulations were required to train the data, and what outputs were used? How many emulations were eventually produced – one for each possible combination of input variables? Are the 10,000 realizations of vertical heating profiles produced using the same combination of input parameters and the same emulator method?

Following Johnson et al. (2015) and Wellmann et al. (2018), we have used $15 \times k$ input combinations to train the emulator, with k the number of input parameters, which is 6 in S1, 7 in S2 and 6 in S3. Furthermore, 10 simulations were added to the training datasets of S1 and S3 to increase the quality of the emulator fit. Thus, per Setup, 100 (S1 and S3) or 105 (S2) simulations were run to generate the training data. Additionally, 45 simulations with other input parameter combinations were conducted per setup for the evaluation of the emulators. This information has been added in section 3.1. The output variables are the ones shown in Figs. 1, 2 and 3: 6 hydrometeor loads, 5 precipitation variables, total diabatic heating rate on 35 vertical levels, and hail size distribution in 10 size bins (i.e. 56 emulations per setup, in total 118 emulations). Regarding the selection of combinations of input parameters, see p. 8: „This is ensured by the use of maximin Latin hypercube sampling (Morris and Mitchell, 1995) to select these input combinations.“ The combinations of input parameters used in the three setups have been added to the published dataset accompanying this study.

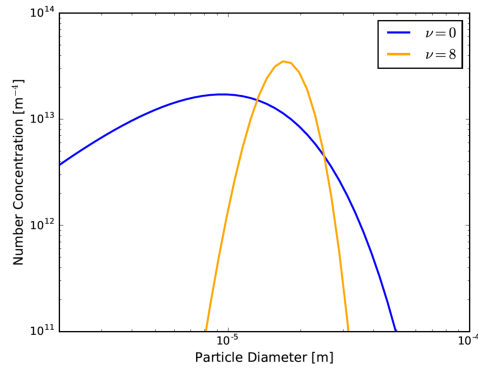
The 10,000 realizations have been produced with the emulators that were derived the same way as the emulators for the hydrometeor loads and precipitation. For clarification, the first paragraph of section 4 has been reformulated: *“In the analysis, we consider several output variables for which emulators are derived as described above. These output variables, including vertically integrated hydrometeor contents, precipitation, diabatic heating rates and the size distribution of surface hail, will be described in more detail in this section.”*

4. The discussion of the variability of the hail size distribution caused by the different input parameters focused solely on the maximum and minimum number concentrations and not the distribution of responses within those bounds. Within Fig. 6, could box and whisker plots be used to show the distribution of number concentrations within each of the three setups within a set range of size bins? That would allow the distribution of distributions, as it were, to be discussed.

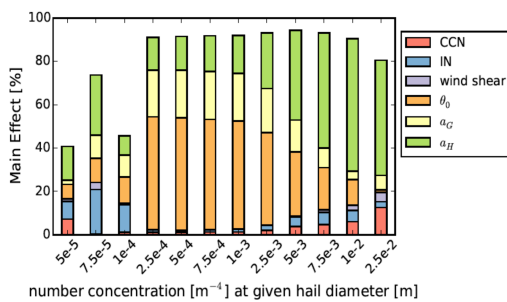
For Fig. 6, the spread is based on 64 parameter combinations with characteristic high and low values, not on 10,000 evenly distributed combinations. The reason for this difference to Fig. 5 is that our aim was to attribute the minimum and maximum hail size distributions to specific parameter distributions. Therefore box and whisker plots would not be well suited here.

To Figs. 3a and 6 I'd also like to see added the range over which $N(D)$ and D are allowed to vary within the microphysical scheme used, for the range of \tilde{A}_o used. That would place the amount of variability in context.

Note that the shape parameter was varied for the droplet size distribution, not for the hail size distribution. Two size distributions with equal mass and shape parameters of $v=0$ and $v=8$ are shown in the below figure, taken from Wellmann (2019). We have decided not to include this figure, because the analytical equation is included and the plot can be easily produced.



I'd also like to see Fig. 3b repeated with the data analyzed in Setup 3 and Fig. 6, as I feel it lets the reader more easily grasp the key ingredients in the output variability.



The figure requested by the reviewer is published in Wellmann (2019), see above. We have decided not to include this figure (and the equivalents of Fig. 1, 2a, 2b and 3a) for setup S3 in order to keep the manuscript concise. Instead, we focus our analysis of S3 entirely on the relative importance of environmental and microphysical parameters and the comparison to S1 and S2, which required different plots (Figs. 4, 5 and 6).

Minor comments: Pg 4, line 7: Do the authors feel 1 km is of a fine enough resolution for this study? From the literature, would they expect any of the results to change if this resolution were reduced?

Many realization of the WK idealized supercell case have been published using a 1 km grid (e.g., Seifert & Beheng, 2006b). Huang et al. (2018) showed in simulations of this case with WRF that precipitation and hydrometeor content are very similar with 1 km grid spacing as with 200 m grid spacing. Potvin and Flora (2015) concluded that 1 km grid spacing produces useful forecasts despite of remaining errors (e.g. in the timing of the storm evolution). As internal cloud dynamics were not the aim of this study, we believe that this resolution is sufficient for our purpose. We have added the following sentence:

“This grid spacing was shown to be sufficient for the simulation of precipitation and hydrometeor content of idealized supercells, although vertical transport and timing differ from simulation at higher resolutions (Potvin and Flora, 2015; Huang et al., 2018).”

Huang, W., J. Bao, X. Zhang, and B. Chen, 2018: Comparison of the Vertical Distributions of Cloud Properties from Idealized Extratropical Deep Convection Simulations Using Various Horizontal Resolutions. *Mon. Wea. Rev.*, 146, 833–851, <https://doi.org/10.1175/MWR-D-17-0162.1>

Potvin, C.K. and M.L. Flora, 2015: Sensitivity of Idealized Supercell Simulations to Horizontal Grid Spacing: Implications for Warn-on-Forecast. *Mon. Wea. Rev.*, 143, 2998–3024, <https://doi.org/10.1175/MWR-D-14-00416.1>

Seifert, A. & Beheng, K., 2006: A two-moment cloud microphysics parameterization for mixed-phase clouds. Part 2: Maritime vs. continental deep convective storms. *Meteorol. Atmos. Phys.* 92: 67. <https://doi.org/10.1007/s00703-005-0113-3>

Pg 4, line 15: A quick sentence here clarifying the difference between saturation adjustment and explicit diffusional growth would be helpful.

We have rephrased the sentence as follows: „Furthermore, the model uses the two-moment bulk microphysics scheme by Seifert and Beheng (2006a), including a saturation adjustment approach (i.e. bringing relative humidity back to exactly 100% within one time step when supersaturation with respect to water occurs), predicting both the mass mixing ratios and the number densities of six hydrometeor classes (cloud droplets, rain, cloud ice, snow, graupel and hail).“

Pg 6, Table 2: Over what intervals were these values varied?

There are no fixed intervals. For the emulator construction, an algorithm implementing maximin Latin hypercube sampling (Morris and Mitchell, 1995) was used to select these input combinations. The combinations of input parameters used in the three setups have been added to the published dataset accompanying this study (doi:10.5445/IR/1000099232).

Pg. 7, line 11: Why is μ held constant?

We follow here Igel and van den Heever (2017a,b). With the dispersion parameter $\mu=1/3$, the general gamma distribution of Seifert and Beheng (2006a) for the cloud droplet mass reduces to a (simple) gamma distribution for the drop diameter, which is the type of distribution used by Igel and van den Heever (2017a,b). We have not been able to find any studies on the spread of the dispersion parameter in observations. An earlier study with the Seifert and Beheng (2006a) cloud scheme (Noppel et al., 2010) has also changed μ , but we think that this additional parameter would not add another dimension of uncertainty to our ensemble.

Pg. 7, line 16: “chosen such that the most important parameters. . .are considered” – how were these chosen?

For clarification, we have added/modified this sentence:

“Based on the results of the sensitivity analysis for hydrometeor and precipitation variables in setups S1 and S2, where the sets of environmental conditions and the cloud microphysics parameters are treated separately (Fig. 5 of Wellmann et al. (2018) and Fig. 1 of this manuscript), the input parameters of this combined Setup 3 (S3) are chosen such that the most important parameters of both environmental conditions and microphysics (those that contribute most to output uncertainty across the selected output variables) are considered in addition to the CCN and INP concentrations.”

Pg. 9, lines 4-7: Nice description.

Thank you.

Pg. 9, Section 4.1, lines 15 – 5: The units of these variables need to be included. Is hail at ground and max hail at ground accumulation-based over the final 5 hours of the simulation? Are the mean and maximum values mentioned calculated in both space and time?

The units are kg m^{-2} for all vertically integrated hydrometeor contents, kg m^{-2} for the maximum accumulated total precipitation and $\text{kg m}^{-2} \text{s}^{-1}$ for the mean and maximum hail at ground per 15 minutes as well as for the maximum precipitation rate of hail and the maximum total precipitation rate.

Maximum and mean values are taken both in space and time (except for accumulated total precipitation, which is integrated over time).

We have added this information to the text, such that it now reads

“The spatial and temporal mean is taken for the considered vertically integrated hydrometeor contents (all in kg m^{-2}). The set of considered precipitation variables include the amount of hail at the ground per output interval of 15 minutes, the precipitation rate of hail and the total precipitation rate (all in $\text{kg m}^{-2}\text{s}^{-1}$) and the accumulated total precipitation (in kg m^{-2}). Precipitation is analyzed similarly to the hydrometeor

masses, but maximum values in space and time are considered instead of mean values. An exception is the amount of hail at the ground, for which both mean and maximum values are analyzed.”

Is precipitation rate of hail a flux of the mixing ratio through the lowest model level?

No, this is the hail reaching the surface.

Pg. 10, Figure 1: Reorder the colors in the bar plot so they are the same order as the legend – many of them are similar shades.

Done.

Pg. 10, line 24: “to examine how the simulated storm impacts the ambient conditions” is an odd phrasing. “Ambient”, to me, indicates the environmental air surrounding the convection. Diabatic heating profiles can modify this region through gravity waves and other atmospheric responses, but here the authors are focused on in-storm effects. I would reword to “examine how the heating profiles of the simulated storm change”.

We have simply changed this to “To examine how the simulated storm impacts the temperature profile, ...”

Pg. 11, line 7: “covering the whole parameter space” – is this the whole input parameter space?

Yes, it is.

Pg. 12, line 4: Instead of number density, should this be number concentration?

As suggested, this has been changed to “number concentration” (also three lines above this occurrence).

Pg. 12, line13: when referring to the “lowest number concentrations of hail”, to what diameter are you referring?

This statement referred to the whole size distribution. To clarify this, we have inserted this information in parentheses: “The lowest number concentrations of hail (over the entire size distribution) are found ...”

Pg. 12, last two sentences: From this figure, it appears to me CCN has a larger effect than the strength of the ice multiplication.

We have emphasized a_H and the ice multiplication factor because both are microphysical parameters and their impact is consistent over the entire size range except for the two largest diameters. The impact of CCN and a_G is also large but varies significantly over the considered size range. This has now been expanded upon:

„The corresponding plot of the main effect (Fig.3, right) confirms the impact of the fall velocity of hail (a_H) and the strength of the ice multiplication together to be responsible for large parts of the output uncertainty of the number concentration at all considered diameters except at $D > 25$ mm. These two parameters contribute more than 50 % to the output uncertainty for these diameters. At the largest considered diameters, an increased contribution from the CCN concentration comes into play, while smaller diameters are also impacted by the graupel fall speed. This may be linked to the two formation pathways of hail in COSMO, namely through freezing of rain (of which the size is impacted by the CCN concentration) and through riming of graupel.“

Pg. 13, Table 3: Per Khain et al. 2011 (Atmospheric Research), the signal of CCN changes associated with hail fall switches sign around 3000 cm-3. Do the authors think their results are in line with this study?

No, as shown and discussed in Wellmann (2018, Fig. 7.13 therein), our results are not in line with Khain et al.’s (obtained from a 2D simulation of a model with a bin microphysics scheme), but rather with Noppel et al (2010), who used also the COSMO model. However, we think that this discussion is out of the scope of this manuscript.

Pg. 14, lines 3-4: I would argue the contribution due to CCN is larger in both S1 and S2 than S3.

The reviewer is correct for the precipitation variables, but not for the hydrometeor contents. However, our statement that S3 is more similar to S2 than to S1 except for cloud water and snow is also correct. We have thus kept the sentence at it is, and have added tables with the numerical values in the appendix (Tables A1 and A2).

Pg. 15, lines 34-40: See specific comment #2.

As indicated above, we have emphasized the importance of the input parameter range once more in the abstract and conclusions. In this paragraph, we think that the two last sentences were already very clear and have been reformulated only slightly: "Furthermore, in our study the parameter range of the wind shear is chosen to reflect typical forecast errors and not a broad range of atmospheric conditions. This results in a smaller impact of the wind shear variation compared to the setup of Dennis and Kumjan (2017)."

Pg. 16, line 10: See specific comment #2.

Here we point out that our results are not directly comparable to the results of Storer et al. (2010) because of different input parameter ranges. We don't see any necessity to change this statement.

Pg. 15, second line 5: it seems like the authors are arguing there is a difference between "the cloud" and "the integrated amount of cloud water" in the Storer et al. (2010) study. Could they explain what his difference is?

This statement has been clarified: "In their study, the updraft strength and the total accumulated precipitation are very sensitive to changes in CAPE, while the integrated amount of cloud water does not depend strongly on CAPE."

Pg. 16, Fig. 5: I'm unable to see the different standard deviation distributions. Perhaps instead a similar plotting method as in Fig. 6, with individual lines of different styles marking the edges of the standard deviations.

We have added horizontal bars for the standard deviation at one selected altitude.

Pg. 17, lines 28-29: Saturation adjustment was not one of the input parameters selected to test, so how can the authors make this claim?

Our sentence was misleading. We have rephrased this to: "Condensation of cloud water, which is a substantial contributor to the total heating rate in the lower and middle troposphere, is parameterized via a saturation adjustment scheme in our model. Nevertheless, it yields a large contribution to output uncertainty of the diabatic heating in all three setups. This effect might be even larger if a time-dependent treatment of condensation was used."

Pg. 17, lines 3-4 (just before section 5.3): See specific comment #2.

We have removed this sentence.

Pg. 18, lines 17-18: Can this sentence be worded more clearly? Perhaps "the spread of the distributions in S2 is larger than S1, particularly for smaller diameters of hail."

To also satisfy reviewer #1, who also had a comment on this sentence, we have reformulated it to "For S2, the low (dashed red line) and high (continuous red line) hail size distributions are smaller and larger, respectively, than those for S1, leading to a larger spread in the distributions."

Can the authors comment why the uncertainty is so much larger for smaller diameters?

This statement is unclear to us. The spread is rather smaller for smaller diameters, not larger.

Pg. 19, first and second lines: The authors note the relationship between low fall velocity of graupel and high number concentrations of hail several times in the paper. Could they provide a physical explanation for this relationship?

We have added tentative explanations:

“low fall velocities of graupel (presumably resulting in more time for riming of graupel and growth to hail) and high fall velocities of hail (possibly by leaving less time for melting below the cloud) lead to high number concentrations.”

Pg. 19, line 20: “than the inputs related to environmental conditions”. . .on the scale of uncertainty seen in COSMO. See specific comment # 2.

We have added “(with the spread of input parameters chosen in this study)”.

Pg. 21, line 23-26: An excellent summary of the potential impact of this research – but it depends on the transferability of the results to other microphysical parameterizations (see specific comment #1).

We agree with the reviewer and have added the following paragraph (as mentioned above): “It can be expected that our results (in particular regarding the microphysical parameters) depend to some extent on the microphysics scheme of our model. However, the overarching aim of this study was not to emphasize the impact of a specific parameter, but to quantify the relevance of environmental versus microphysical uncertainty in general. We expect that these results are less dependent on the microphysics scheme.”

Typographical: Pg. 4, line 31: Add a comma after profile. Pg. 10, Eq. 3: instead of ν/s , which denotes division, I'd use ν_s .

All of these have been corrected.

Pg. 10 line 34: “such that”-> where

This would change the meaning of the sentence. However, we decided to omit the second half of this sentence entirely, because it doesn't give any new information.

Anonymous Referee #3

Review of “Comparing the impact of environmental conditions and microphysics on the forecast uncertainty of deep convective clouds and hail” by Wellmann et al.

The study identifies model input parameters describing environmental conditions and cloud microphysics that lead to large uncertainties in the prediction of deep convective clouds and precipitation, by conducting statistical emulation and variance-based sensitivity analysis of the simulated deep convective clouds in an idealized setup of a cloud-resolving model. They showed some interesting results that could be useful in guiding the improvement of forecasting. However, the results could be very dependent of microphysics scheme, model setup (such as idealized vs. real, nesting vs non-nesting), and even convective case. This discussion would be necessary. Particularly, the two moment microphysics schemes with saturation adjustment for condensation/evaporation calculation could lead to very different CCN impacts on latent heating and precipitation rate compared with more explicit microphysics schemes such as bin scheme as detailed in a review article (Fan et al., 2016, JAS). This could change the conclusion related to the diabatic heating rate. Another major problem of this manuscript is that the authors only described what the figures show, and did not interpret the results by connecting with physics properties/processes. See my specific comments for Section 4 and 5. The paper also has quite a bit of confusing statements that need to be clarified. Therefore, a major revision is recommended to improve the paper before it is accepted for publication.

We agree that the details of the parameterizations employed here have the potential for a significant impact on the results. However, our main aim was not to emphasize the impact of a specific parameter, but rather to weigh the relevance of environmental versus microphysical uncertainty. We expect that this result is less dependent on the microphysics scheme.

We have added the following paragraph to the conclusions: “It can be expected that our results (in particular regarding the microphysical parameters) depend to some extent on the microphysics scheme of our model. However, the overarching aim of this study was not to emphasize the impact of a specific parameter, but to quantify the relevance of environmental versus microphysical uncertainty in general. We expect that these results are less dependent on the microphysics scheme.”

Furthermore, we agree with the reviewer that the saturation adjustment scheme in our model may lead to an overestimation of condensation and latent heating. The uncertainty related to condensation may be underestimated. This is now stated more explicitly in the conclusions: “Condensation of cloud water, which is a substantial contributor to the total heating rate in the lower and middle troposphere, is parameterized via a saturation adjustment scheme in our model. Nevertheless, it yields a large contribution to output uncertainty of the diabatic heating in all three setups. This effect might be even larger if a time-dependent treatment of condensation was used.”

Also regarding the expected dependence on the case and setup, we agree with the reviewer. However, more complex setups would have been computationally more expensive, and also more difficult to analyse. To our knowledge, no study exists in which emulators have been developed for real or nested cases. Therefore we think that an extension of this work into the direction of more and more complex cases would be desirable, but is out of the scope of the present manuscript. We have added “This rather simple setup was required to allow a large number of simulations in which environmental conditions and microphysical parameters are modified.”

And in the last paragraph: “In addition, future studies should address how far the results of our idealized simulations are transferable to real cases.”

Specific comments

The title has a grammatical error: it should be “Comparing . . . to (or with) . . .”

According to Merriam-Webster, “comparing apples and/to/with oranges” all are acceptable. Reformulating the title as suggested would make it significantly longer, and we have therefore decided to keep it as it is.

Abstract:

Need some detailed background about how change of environmental conditions affect deep convective cloud properties. P1, L8-9 I think the results section showed that fall speed of graupel even contributes more than the fall speed of hail. In the last sentence, suggest rewrite or add sentence to show what parameters impact hail.

We have rewritten the second but last sentence and now explicitly mention the role of the graupel fall speed. Regarding more detailed background information, we think that this is better placed in the introduction than in the abstract.

Introduction:

1. P1, L16, Fan et al., JGR, 2009 and Qian et al., JGR, 2015 are the studies focusing on wind shear impacts on convective clouds.

We have added the suggested references, but note that this list was not meant to be exhaustive.

2. P2, L5, Change the second "for" to "with".

Done.

3. P2, L22-23 The sentence "However, the impact on precipitation is not identified as the investigated clouds are non-precipitating" needs to be rewritten. I have no idea what you want to say here.

We meant that the clouds simulated by Igel and van den Heever (2017) were non-precipitating and therefore, this study made no statements on the impact of the cloud drop size distribution shape parameter on precipitation. We have removed this sentence and inserted two words in the previous sentence: "Igel and van den Heever (2017) vary the shape parameter of the cloud droplet size distribution in simulations of non-precipitating shallow cumulus clouds."

4. P2, L25, The sentence "because of its higher fall velocity immediately falls out of the cloud leading to reduced convection intensity" has grammar errors and also confusing.

This sentence has been reformulated to "Their results show that "hail-like" (large and dense, with a high fall velocity) graupel immediately falls out of the cloud, leading to a reduced convection intensity."

5. Need to change the strong tone in some statements., for example,

(1) "There are only a few studies including Lee et al. (2008) and Storer et al. (2010) where the effect of several parameters is analyzed", you do not need to say only a few studies since there are a significant number as far as I know. If indeed just a few, all of them are needed to be cited here. (2) "The only previous studies of multiple interacting uncertainties in deep convective clouds are our own previous study (Wellmann et al., 2018) and Johnson et al. (2015)."

In the first of the mentioned sentences, we have changed "only a few" to "a few". Regarding the second statement, we believe that this is correct, but we have clarified that we refer here to studies with multiple (six or more) interacting parameters. With a few other reformulations, this paragraph now reads:

"The development of deep convective clouds is sensitive to both environmental conditions and model parameters, but these sensitivities are usually examined separately. A few studies, including Lee et al. (2008) and Storer et al. (2010), have analyzed the effect of several parameters, yet the maximum number of considered parameters is three or less. In this study, we combine various parameters related to both environmental conditions and microphysics into a single comprehensive sensitivity analysis. In idealized high-resolution model simulations, the selected input parameters are modified and their effect on the model output is analyzed with a special focus on precipitation and thermodynamic quantities. To our knowledge, the only previous studies of multiple (six or more) interacting uncertainties in deep convective clouds are our own previous studies (Wellmann et al., 2018; Johnson et al., 2015)."

Model Setup:

1. Since the open lateral boundaries are used, need to specify how the boundaries are set up, i.e., what are used for the boundary conditions?

We specify this a couple of sentences later:

"The initial temperature and humidity profiles (which are also used when air is advected into the domain through the boundaries) are based on those of Weisman and Klemp (1982)."

2. P4, L20 How did you define cloudy points?

This has been added:

"where the vertically integrated content of any hydrometeor type is >0 "

3. P4, L34-35, the recent progress about CCN impacts on convective clouds is Fan et al., (2018, Science).

Instead of adding a 10th reference for this rather simple statement, we have inserted "e. g." and reduced the number of references to 3. Our original list was by no means meant to be exhaustive.

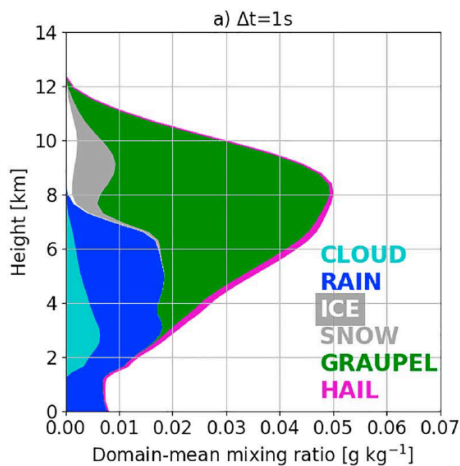
4. P5, L15-16, this is confusing, how can you specify the wind velocity to be constant in all simulations since wind is a prognostic field?

This refers only to the initial profile. This has been clarified.

Sections 4 and 5:

1. I think some brief introduction to the case is needed before discussing the results from uncertainty quantification (UQ), which would help understand the UQ results. For example, I would like to know the relative amount of each hydrometeor mass to understand if this is a hailstorm case or not (i.e., hail mass is dominant compared with graupel mass). This would help me understand why graupel fall speed is the largest contributor to the uncertainty of integrated hydrometeor mass.

As our ensemble encompasses a wide range of parameter values, it is not possible to describe "the" case. One example realization is depicted in this figure from Barrett et al. (2019). Most cases have more graupel than hail aloft, but this reverses at lower levels. We think that the reason why graupel fall speed is so important lies in the formation pathway of hail by riming of graupel.



2. In both Section 4 and 5, there is a problem that the authors only describe the figures, but do not interpret the results from physics perspective. For example, in describing Fig. 1, it is better to understand why graupel fall speeds and CCN have the largest impacts on integrated hydrometeor mass but not on the hail mass? Why CCN have a large contribution to integrated hydrometeor mass but not to diabatic heating?

We agree with the reviewer that more discussion of the physical processes was necessary. However, it is difficult to derive causal relationships from our statistical analysis. Therefore, most explanations are speculative, and we have indicated this wherever necessary.

Regarding the CCN impact on hydrometeor contents, we have added: "The second most important parameter is the CCN concentration, which contributes especially to the uncertainties of cloud water (because it determines autoconversion and thus impacts the partitioning between cloud and rain water) and snow content."

And in section 4.2: “CCN contributes only modestly to uncertainty at these levels, although the heating rate by condensation is very strong here. This is probably linked to the fact that a saturation adjustment scheme is used for cloud condensation, which is thus insensitive to droplet number and size.”

3. I have a hard time to physically understand the contributions shown in Figure 2. At the maximum heating around 3-6 km, the latent heating should be dominated by condensation, which should be strongly affected by CCN. But because saturation adjustment is used for condensation and evaporation, the CCN effect on condensation is not shown here. This problem should be discussed.

See above.

In addition, How does graupel and rain fall speed contribute to the heating uncertainty? Above 10 km, the major contributors are CCN and graupel fall speed. I think it is because they affect how much amount of condensate mass are being transported to the upper levels. This kind of discussion is important to connect with cloud physics.

We agree with the interpretation of the reviewer. The text we have added reads: “Above [10 km], the output uncertainty of the total heating rate is dominated by the CCN concentration and the fall velocity of graupel. This is probably linked to the indirect effect of CCN and riming efficiency on the amount of supercooled water transported to the homogeneous freezing level. Furthermore, graupel is produced at these levels in our model as a result of the freezing of rain drops, and the graupel fall speed factor thus impacts the gravitational sink of the (small) graupel particles present at these altitudes.”

4. P12, L18-20 Figure 3 shows the largest contribution is graupel and hail fall speeds, which is different from what is described here.

In this sentence, we have emphasized the parameters which are important for the entire size range of hail. The graupel fall speed is important only for the smaller diameters. The paragraph has been reformulated to clarify this and to add some physical explanation:

“The corresponding plot of the main effect (Fig. 3, right) confirms the impact of the fall velocity of hail (a_H) and the strength of the ice multiplication together to be responsible for large parts of the output uncertainty of the number concentration at all considered diameters except at $D < 25$ mm. These two parameters contribute more than 50 % to the output uncertainty for these diameters. At the largest considered diameters, an increased contribution from the CCN concentration comes into play, while smaller diameters are significantly impacted by the graupel fall speed. This may be linked to the two formation pathways of hail in COSMO, namely through freezing of rain (of which the size is impacted by the CCN concentration) and through riming of graupel.”

5. P12, L20-21, need to discuss the possible physical mechanisms of how CCN affect the large hailstones. There are literature studies about this.

We are unsure which references the reviewer refers to. As obvious in our answer to item 4, we refer here to the hail formation processes in our microphysical scheme.

6. P15, the first three paragraphs, need some discussion in connecting with cloud physics to understand why. For the third paragraph, how to explain the contrasting contribution of hail fall speeds to hydrometeor mass and precipitation?

The first paragraph now includes a statement on the possible mechanism for the suppression of sensitivity to INP: “Thus, the main effect of the INP concentration is smaller if other microphysical parameters are used as input, possibly because other ice phase processes (secondary ice formation, riming) can suppress the sensitivity of a cloud to primary ice formation.”

The third paragraph has been revised as follows: “When looking at the hydrometeor masses, the contribution from the fall velocity of hail to the output uncertainty is negligible except for the integrated hail and rain contents. However, it is the largest contributor to the uncertainty of the precipitation variables, presumably reflecting that hail itself and melted hail constitutes a major part of the total precipitation.”

7. P17, “Dennis and Kumjian (2017) specify in their work that process rates are not an essential factor causing discrepancies in the formation of hail for different model setups”, not sure what this means, since microphysical process rates directly determine the budget.

We agree that this sentence was confusing, and have removed it.

8. Section 5.3, need clearer introduction here to state the purpose of this part. I was not understanding the purpose of this part until I got to the summary (last paragraph of page 20).

We have moved part of the last sentence of p. 20 to the beginning of section 5.3: “In this section, we analyze the impact of variations of environmental conditions and microphysical parameters on the size distribution of surface hail.”

9. P18, L12-21, all of the magnitudes described in these two paragraphs are different from what is shown Figure 6. For example, the maximum value plotted is $0.01 \text{ mm}^{-1}\text{m}^{-3}$, but you got values of 0.4 and $3.4 \text{ mm}^{-1}\text{m}^{-3}$ in the text. Need to check what is going on.

We apologize for this mistake. The numbers in the text were wrong and have been corrected.

10. P18, L15-16, the sentence is confusing and need clarifications.

For clarification, this sentence has been split into two sentences: “For this setup (in which the environmental conditions are modified), the controlling parameters are the CCN and INP concentrations and θ_0 . Low number concentrations of hail arise for higher values of these parameters and high number concentrations of hail for lower values.”

Section 6:

1. The relevant summary (the first three paragraphs) needs to be revised accordingly by adding physical explanations.

As the summary mostly describes microphysical and environmental parameters as a package, we therefore think that iterations on our thoughts on the underlying processes for the effects of individual parameters would not be well placed here.

Where CCN and graupel fall speed are mentioned, we have added “These parameters are crucial for the efficiency of warm and cold rain formation, respectively.”

2. For “The controlling parameters of the combined input parameters are the INP concentration and the fall velocities of graupel and hail, hence a combination of parameters describing environmental conditions and microphysical parameters”, the logic of the sentence is wrong. All the parameters described here are only microphysical parameters.

We removed “hence a combination of parameters describing environmental conditions and microphysical parameters” to avoid confusion, but note that in our setup S1, INP concentration is counted as an environmental parameter because it characterizes the aerosol environment (different from the other microphysical parameters, which refer to uncertain microphysical parameterizations).

Comparing the impact of environmental conditions and microphysics on the forecast uncertainty of deep convective clouds and hail

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Abstract. Severe hailstorms have the potential to damage buildings and crops. However, important processes for the prediction of hailstorms are insufficiently represented in operational weather forecast models. Therefore, our goal is to identify model input parameters describing environmental conditions and cloud microphysics, such as vertical wind shear and strength of ice multiplication, which lead to large uncertainties in the prediction of deep convective clouds and precipitation. We conduct a comprehensive sensitivity analysis simulating deep convective clouds in an idealized setup of a cloud-resolving model. We use statistical emulation and variance-based sensitivity analysis to enable a Monte Carlo sampling of the model outputs across the multi-dimensional parameter space. The results show that the model dynamical and microphysical properties are sensitive to both the environmental and microphysical uncertainties in the model. The microphysical parameters, especially the fall ~~velocity~~ of velocities of graupel and hail, lead to larger uncertainties in the output of integrated hydrometeor ~~masses~~ mass contents and precipitation variables. In contrast, variations in the environmental ~~conditions~~ parameters — the range of which is limited to represent model uncertainty — mainly affect the vertical profiles of the diabatic heating rates.

Copyright statement. TEXT

1 Introduction

Due to the large damage potential associated with severe convective storms, the forecast of deep convective clouds should be as accurate as possible. Thus, numerous studies have been published on simulating deep convective clouds, ~~where it has been investigated how various parameters such as the concentration of cloud condensation nuclei (CCN) or ice nucleating particles (INP) or vertical wind shear.~~ These have investigated how environmental parameters like wind shear (e.g., Weisman and Klemp, 1984; Lee and the aerosol environment, which determines the CCN concentration (e.g., Lee et al., 2008; Rosenfeld et al., 2008; Fan et al., 2013), affect the clouds in these simulations ~~(Weisman and Klemp, 1984; Lee et al., 2008; Rosenfeld et al., 2008; Fan et al., 2013; Dennis and Ku~~

In Wellmann et al. (2018) we investigated the impact of simultaneous variations of six parameters describing environmental conditions. These parameters include CCN and INP concentrations, wind shear, thermodynamic profiles and two parameters characterizing the trigger mechanism used to initiate convection. The results showed that integrated hydrometeor ~~masses~~ mass contents and precipitation are most sensitive to variations of the CCN concentration and the vertical temperature profile.

Moreover, different mechanisms for ~~triggering convection~~ artificially triggering convection (a warm bubble, a cold pool or a bell-shaped mountain ridge) are compared revealing that the sensitivities depend on the choice of the trigger.

~~Not only~~ In addition to thermodynamic profiles and environmental conditions ~~affect~~ determining the formation and structure of deep convective clouds, ~~but also the microphysical parameterizations~~ also microphysical parameterizations have been shown to play a role. White et al. (2017), for example, simulate three cloud types ~~for the Morrison~~ using the Morrison (Morrison et al., 2005, 2009; Mor, 2011) and the Thompson (Thompson et al., 2004, 2008) bulk microphysics schemes varying the cloud droplet number concentration. They find that the use of the two schemes causes larger differences than the changes in the number concentration. ~~Besides the microphysics schemes themselves, individual parameters included in these schemes substantially affect the output in terms of different precipitation variables,~~ primarily because of the representation of autoconversion of cloud water to rain and of cloud ice to snow. Splinters of ice particles, which can be generated during the riming process, favor the growth of ice from both the vapor and liquid phase because of their crystal lattice structure (Houze, 1993). This process of secondary ice production was introduced by Hallett and Mossop (1974) and is thus referred to as the Hallett-Mossop process. Connolly et al. (2006) simulate a thunderstorm over northern Australia to examine the impact of CCN and INP concentrations including variations of the strength of the Hallett-Mossop process. The results show that the height of the cloud top depends on the strength of the Hallett-Mossop process, whereas the mean precipitation is rather insensitive to these changes. In Johnson et al. (2015) the sensitivity of twelve deep convective cloud properties to uncertainties in nine microphysical processes is studied in a spectral bin microphysics model, using an emulator approach. They find that the cloud properties, including accumulated precipitation and maximum precipitation rates, are sensitive to a combination of aerosol concentrations and microphysical assumptions in the model.

~~Further~~ Additional relevant parameters are the size distributions and the fall speeds of hydrometeors. ~~In their study, ?~~ Igel and van den Heuvel (2018) investigate the impact of graupel size and thus also of the fall speed on deep convection. Their results show that “hail-like” graupel, which tends to be larger and denser, because of its higher fall velocity (large and dense, with a high fall velocity) graupel immediately falls out of the cloud leading to, leading to a reduced convection intensity. In contrast, smaller and slower falling graupel particles stay longer in the cloud, which results in more persistent convection. Also the results of Johnson et al. (2015) indicate that the fall speed of graupel is an important parameter influencing the precipitation rate. Moreover, field studies indicate that fall speeds of hydrometeors are observed in study observations indicate that hydrometeors may have a broad range of velocities (Knight and Heymsfield, 1983; Yuter et al., 2006; Heymsfield et al., 2018) fall velocities (Knight and Heymsfield, 1983; Yuter et al., 2006)

which implies that there is large uncertainty in the result of the model parameterizations of the fall speeds. ~~Not only Gilmore et al. (2004) and Posselt and Vukicevic (2010) vary both~~ the fall speeds ~~but also and~~ the densities of hail/graupel and snow ~~are varied by Gilmore et al. (2004), Posselt and Vukicevic (2010), who, and~~ find that these parameters impact the amount of precipitation significantly.

5 The development of deep convective clouds is sensitive to both environmental conditions and model parameters, but these sensitivities are usually examined separately. ~~There are only a few studies~~ A few studies, including Lee et al. (2008) and Storer et al. (2010) ~~where, have analyzed~~ the effect of several parameters ~~is analyzed~~, yet the maximum number of considered parameters is three or less. In this study, we combine various parameters related to both environmental conditions and microphysics ~~into~~ a single comprehensive sensitivity analysis. In idealized high-resolution model simulations, the selected
10 input parameters are modified and their effect on the model output is analyzed with a special focus on precipitation and thermodynamic quantities ~~is analyzed. The~~. To our knowledge, the only previous studies of multiple (six or more) interacting uncertainties in deep convective clouds are our own previous ~~study (Wellmann et al., 2018) and Johnson et al. (2015)~~ studies (Wellmann et al., 2018; Johnson et al., 2015).

In general, the approach usually applied for the analysis of the sensitivity of the model output to changing input parameters
15 is to vary a chosen parameter in a given range while other parameters are kept constant. This so-called *one-at-a-time* (OAT) analysis is applicable if the impact of a single model input is of interest. However, not only the effect of each input parameter independently will be assessed in this study, but also the relative contribution of the input parameters and their interactions to the whole uncertainty of the output is of interest. In reality, severe convective storms form in a wide range of ~~different~~
ambient conditions, where ~~for example, sometimes thermodynamic conditions are the main drivers, sometimes dynamic~~
20 ~~conditions; either thermodynamic conditions or dynamic conditions may be the main driver~~, leading to different organizational forms of the storms. The gradual and combined variation of various parameters better represents real conditions compared to the OAT approach. To achieve this, we apply the methods of statistical emulation (O'Hagan, 2004, 2006) and variance-based sensitivity analysis (Saltelli, 2008), where the uncertainty of the output is densely sampled and then decomposed into contributions from the individual model input parameters while simultaneously considering their interactions. Thereby the
25 relative contributions of each parameter to the uncertainty of the output can be quantified. The applicability of this approach for complex atmospheric models is demonstrated in Lee et al. (2013) and Johnson et al. (2015). Wellmann et al. (2018) also use this approach to investigate how environmental conditions impact the model output when simulating deep convective clouds. They quantify the contributions of parameters describing environmental conditions to the uncertainties of the integrated hydrometeor ~~masses~~ masse contents, precipitation and the size distribution of surface hail. In addition, the emulators are used
30 to examine the sensitivity to changing CCN concentrations in different regimes of environmental conditions and the results are compared for three trigger mechanisms of deep convection, i.e. a warm bubble, cold pool and orography.

Here, we focus on the warm bubble as the trigger mechanism as it is frequently used in idealized studies, but we extend the set of uncertain input parameters to include not only environmental conditions but also microphysical parameters. Consequently, we compare the impact of environmental conditions and microphysics to quantify the individual contributions of the
35 various parameters to the forecast uncertainty of precipitation-related quantities including hail. We also consider the vertical

profiles of the diabatic heating rates in our analysis. This analysis and the choice of output variables are based on the results of the first author's PhD thesis (Wellmann, 2019) wherein more detailed descriptions are given.

A general description of the model setup and the input parameters is given in section 2, followed by an explanation of the methods of statistical emulation and variance-based sensitivity analysis in section 3. The considered output variables are described in section 4 and the results of the sensitivity analyses are presented in section 5. Conclusions are found in section 6.

2 Model Setup

For the simulations in this study, the limited-area numerical weather prediction model COSMO (Consortium for Small-Scale Modeling) (Baldauf et al., 2011; Schättler et al., 2016) developed by Deutscher Wetterdienst (DWD) and the COSMO consortium is used. Identical to Wellmann et al. (2018), we run COSMO in a convection-resolving idealized setup covering a domain of 700×500 grid points with a horizontal ~~resolution-grid spacing~~ of 1 km. This grid spacing was shown to be sufficient for the simulation of precipitation and hydrometeor mass content of idealized supercells, although vertical transport and timing differ from simulation at higher resolutions (Potvin and Flora, 2015; Huang et al., 2018). There are 64 vertical levels extending to a height of 23 km. These levels follow the transformation given in Gal-Chen and Somerville (1975) such that they are denser near the ground and further apart with increasing height ~~-(approximately 300 m vertical distance at 5 km altitude and 400 m vertical distance at 10 km altitude).~~ Variables are written out and analysed on interpolated z-levels with 250 m vertical distance up to 3 km and 500 m vertical distance above. Open boundary conditions are used to prevent a simulated hailstorm from influencing itself via reflection at the boundaries. Moreover, we switch off the radiation scheme and neglect the Coriolis force in the simulations. The initial temperature and humidity profiles ~~are-(which are also used when air is advected into the domain through the boundaries) are~~ based on those of Weisman and Klemp (1982) to maintain atmospheric conditions favoring the development of deep convection. According to their profile, the maximum specific humidity q_{v0} is chosen to be 12 g kg^{-1} at the lowest level. The vertical wind profile is comparable to the hodograph of quarter-circle shear introduced by Weisman and Rotunno (2000). Furthermore, the model uses the two-moment bulk microphysics scheme by ~~Seifert and Beheng (Seifert and Beheng, 2006a)-making use of saturation adjustment is implemented in the idealized setup~~ Seifert and Beheng (2006a), including a saturation adjustment approach (i.e. bringing relative humidity back to exactly 100% within one time step when supersaturation with respect to water occurs), predicting both the mass mixing ratios and the number densities of six hydrometeor classes (cloud droplets, rain, cloud ice, snow, graupel and hail). In our simulations, deep convection is triggered by a warm bubble as this mechanism is widely used in atmospheric modeling. The bubble is released at $\Delta x = 80 \text{ km}$ and $\Delta y = 200 \text{ km}$ at model initialization. We run the simulations for six hours with a time step of $\Delta t = 6 \text{ s}$, where the first hour of the simulations is regarded as spin up and thus excluded from the analysis. ~~In addition, we~~ During this simulation period, the clouds do not reach the boundaries of the domain. We consider only cloudy grid points (where the vertically integrated mass content of any hydrometeor type is > 0) in our analysis of the vertically integrated hydrometeor

We have taken a staged approach to our analysis of the effects of uncertain inputs on model output uncertainty for COSMO. We first explored the effects of the environmental conditions (section 2.1), and the full analysis for this study is given in Wellmann et al. (2018). Building on this work, we used the same approach to consider the corresponding effects of microphysical parameters in isolation (section 2.2). We then constructed a further final ensemble (section 2.3) using only the key inputs in the two former studies of the setup with variation of environmental conditions and the new setup with variations in microphysical parameters, in order to enable a comparison of the relative importance ~~between the environmental conditions and microphysical parameters of environmental and microphysical uncertainties~~ for model output uncertainty. Note that as the results depend crucially on the ranges over which the parameters are varied, these have to be chosen carefully and taken into account when comparing to other studies.

2.1 Setup 1 - Varying environmental conditions

The input parameters of interest in this study are assigned to either describe environmental conditions, microphysics or both, where the parameter ranges relate to observations and model uncertainty. Regarding the environmental conditions, CCN concentration, INP concentration, wind shear, vertical temperature profile, and characteristics of the warm bubble, in terms of temperature perturbation and horizontal radius, are perturbed. An overview of these parameters and their respective ranges is given in Table 1. These parameters are referred to as *Setup 1* (S1).

Table 1. Overview of the uncertain input parameters and their ranges regarding environmental conditions (Setup 1). The parameters marked by * are included in Setup 3 which combines environmental conditions and microphysical parameters.

input	min	max	units
CCN concentration *	100	4000	cm^{-3}
INP concentration *	0.01	10	scaling factor
wind shear (F_{shear}) *	0.3333	0.6666	scaling factor
potential temperature at the ground θ_0 (WK profile) *	299	301	K
temperature perturbation ΔT	2	5	K
horizontal radius R_{hor}	5	15	km

CCN, essential for the formation of cloud droplets, affect the dynamics and microphysics of the clouds (Cui et al., 2006; Seifert and Behn). The cloud droplet activation scheme implemented in COSMO is based on grid-scale supersaturation and empirical power law activation spectra and uses look-up tables introduced by Segal and Khain (2006). Moreover, the vertical profile of the aerosol concentration has its maximum in the lowest 2 km above the ground and follows an exponential decrease with a scale height of

1 km towards higher altitudes. We vary the maximum CCN concentration between 100 cm^{-3} and 4000 cm^{-3} simulating both maritime-clean and polluted conditions. INPs affect the number of ice particles in the cloud as they support the formation of cloud ice (Houze, 1993), comparable to CCN generating cloud droplets. For INP changes, a scaling factor is applied to three microphysical processes. These processes are the deposition nucleation of cloud ice, the immersion freezing of cloud droplets and the immersion freezing of rain. The heterogeneous ice nucleation scheme of Huffman and Vali (1973) is implemented for the formation of cloud ice, while a stochastic model following the measurements of Bigg (1953) is used for the freezing of cloud droplets and rain. In this study, the scaling factor is varied between 0.01 and 10 on a logarithmic scale. This range is chosen according to DeMott et al. (2010) representing the range of INP concentrations measured in different field campaigns. We apply the same value of the scaling factor to all three processes.

According to several observational and modeling studies, directional shear is most important for the organization of convection (Weisman and Rotunno, 2000; Davies-Jones, 2015; Dennis and Kumjian, 2017). Therefore, we choose the initial vertical profile of the wind velocity to be constant in all simulations, whereas a scaling factor F_{shear} determines the initial vertical profile of the wind direction $\neg(WD)$:

$$WD(z) = \begin{cases} 270^\circ - F_{shear} \cdot 90^\circ (1 + \frac{z}{6000 \text{ m}}) & , z \leq 6000 \text{ m} \\ 270^\circ & , z > 6000 \text{ m} \end{cases} \quad (1)$$

Depending on the choice of F_{shear} , the wind direction near the ground is set. It linearly turns towards western directions with increasing height until a straight westerly flow is reached at a height of 6 km. For example, $F_{shear} = 0$ represents westerly wind at all heights and $F_{shear} = 1$ specifies southerly wind near the ground. However Here, we vary F_{shear} only between 0.3333 and 0.6666, corresponding to a wind direction at the ground between 210° and 240° , which reflects the typical error range of the operational COSMO forecast of the wind direction (Felix Fundel, personal communication, 2017).

The vertical profile of the potential temperature ~~, which favors the initiation of deep convection,~~ is implemented according to Weisman and Klemp (1982):

$$\theta(z) = \begin{cases} \theta_0 + (\theta_{tr} - \theta_0) \left(\frac{z}{z_{tr}} \right)^{5/4} & , z \leq z_{tr} \\ \theta_0 \exp \left(\frac{g}{c_p T_{tr}} (z - z_{tr}) \right) & , z > z_{tr} \end{cases} \quad (2)$$

It is based on the near-surface potential temperature θ_0 initially set to 300 K, along with the tropopause height z_{tr} and the tropopause temperature T_{tr} . In our study, θ_0 takes values between 299 K and 301 K representing the typical error range of the operational temperature forecast of the COSMO model (Felix Fundel, personal communication, 2017). This variation of θ_0 impacts the entire tropospheric profile and corresponds to a change of the convective available potential energy (CAPE) from 1210 J kg^{-1} to 1347 J kg^{-1} .

The warm bubble is characterized by a temperature perturbation ΔT and a radius R_{hor} . Its maximum temperature perturbation ΔT is located in the center of the bubble and varies between 2 K and 5 K. The horizontal radius ranges between $R_{hor} = 5 \text{ km}$ and $R_{hor} = 15 \text{ km}$, while the vertical extent is fixed at $R_z = 1400 \text{ m}$. The variation of ΔT and the radius alter the strength of the trigger as different buoyancy gradients arise.

As the wind shear and the temperature are part of the operational forecast, their parameter ranges are the only ones that can be related to typical forecast errors. The ranges of the remaining parameters cover a wide variety of atmospheric conditions since there is no information from a forecast. These specifications are identical to those of the sensitivity analysis related to typical forecast errors in Wellmann et al. (2018).

5 2.2 Setup 2 - Varying microphysical parameters

The microphysical parameters analyzed in Setup 2 (S2) are the fall velocities of rain, graupel and hail, the strength of the ice multiplication and the shape parameter of the size distribution of cloud droplets. In addition, the CCN and INP concentrations are included in this set of input parameters. Table 2 summarizes the input parameters of Setup 2 and their considered ranges.

Table 2. Overview of the uncertain input parameters and their ranges regarding cloud microphysics (Setup 2). The parameters marked by * are included in Setup 3 which combines environmental conditions and microphysical parameters.

input	min	max	units
CCN concentration *	100	4000	cm^{-3}
INP concentration *	0.01	10	scaling factor
fall velocity of rain (a_R)	0.3	1.7	scaling factor
fall velocity of graupel (a_G)*	0.3	1.7	scaling factor
fall velocity of hail (a_H)*	0.7	1.3	scaling factor
ice multiplication	$0.1 \cdot 10^8$	$7 \cdot 10^8$	kg^{-1}
shape parameter	0	8	-

The fall velocities of the precipitating hydrometers rain, graupel and hail are implemented in the model following mainly empirical equations based on measurements that describe the relation between the size or other characteristics of the particles and their fall velocities (Locatelli and Hobbs, 1974; Knight and Heymsfield, 1983). This uncertainty propagates in the microphysics scheme as the fall velocity impacts collision processes such as accretion and riming. To assess the uncertainty, scaling factors are multiplied with the fall velocities of rain (a_R), graupel (a_G) and hail (a_H). The ranges of the scaling factors are chosen based on the measurements of Yuter et al. (2006) and Knight and Heymsfield (1983) which suggest a spread of about 70% around the mean of the fall velocities of rain and graupel and a spread of about 30% of the fall velocity of hail, respectively. The production of ice splinters during the riming process introduced by Hallett and Mossop (1974) is a source of secondary ice particles. As their measurements show a large spread (Hallett and Mossop (1974), Fig. 2), we vary the splintering coefficient in the COSMO model describing the number of secondary ice particles per kg rime between $0.1 \cdot 10^8 \text{ kg}^{-1}$ and $7 \cdot 10^8 \text{ kg}^{-1}$ to represent the range of their measurements. The size distribution of the hydrometeors has a substantial impact as various microphysical processes such as condensation or sedimentation depend on this. Thus, uncertainties in the size distributions have several possibilities to affect the processes in the microphysics scheme. By modifying the shape parameter of the cloud droplet

size distribution, we assess the variation of the model output due to these input uncertainties. In the two-moment scheme of COSMO, the size of the cloud droplets is described by a generalized Γ -distribution (Seifert and Beheng, 2006a), where μ and ν are shape parameters of the distribution (see also Section 4.3). The default values are $\mu = 0.3333$ and $\nu = 0.0$, respectively. Here, μ is kept at its initial value, while ν is varied between 0 and 8 similar to Igel and van den Heever (2017a, b) who based their choice on the results of several measurement campaigns. This variation of the shape parameter changes the size distribution between broad distributions with lower number concentrations and narrow distributions with higher number concentrations.

2.3 Setup 3 - Combined varying environmental conditions and microphysical parameters

Based on the results of the ~~previous two setups~~ sensitivity analysis for hydrometeor and precipitation variables in setups S1 and S2, where the sets of environmental conditions and the cloud microphysics parameters are treated separately (Fig. 5 of Wellmann et al. (2018) and Fig. 1 of this manuscript), the input parameters of this combined Setup 3 (S3) are chosen such that the most important parameters of both environmental conditions and microphysics (those that contribute most to output uncertainty across the selected output variables) are considered in addition to the CCN and INP concentrations. The less important input parameters of S1 and S2 have not been reconsidered in order to limit the computational effort for conducting S3. For the variations of the environmental conditions, the parameters identified to affect the uncertainty most are the vertical wind shear and the potential temperature θ_0 (Wellmann et al., 2018). The relevant parameters of the microphysics setup are the fall velocity of graupel and the fall velocity of hail (section 4). Detailed descriptions of these input parameters were already given in sections 2.1 and 2.2, and the same parameter ranges are used. The parameters included in S3 are marked by * in Tables 1 and 2. ~~A study combining all parameters of S1 and S2 would have led to a larger training data set and thus an increase of computational effort, which we want to avoid using the emulators.~~

3 Methods

We identify the parameters leading to the uncertainty in each model output via a variance-based approach, which is a global sensitivity analysis meaning that all of the multi-dimensional parameter space is sampled (Saltelli, 2008). The output uncertainty is decomposed into contributions from each input parameter individually and also contributions from interactions of the parameters (see section 3.2). However, a large number of simulations is required to infer those contributions, which is not feasible for a complex numerical weather prediction model such as COSMO because of the high computational cost. Instead, we employ the approach of statistical emulation to build a surrogate model based on a set of training data. The emulator represents the relationship between a set of input parameters and a specific model output substantially reducing the number of model runs required to generate the data necessary for the variance-based sensitivity analysis. The following two sections give a summary of the emulator approach using Gaussian processes and the variance-based sensitivity analysis. More detailed descriptions of these methods are given in O'Hagan (2004, 2006); Saltelli et al. (1999); Johnson et al. (2015) and Wellmann et al. (2018).

3.1 Gaussian process emulation

First, a set of uncertain input parameters including their respective ranges has to be defined. Depending on the number of input parameters, a choice of input combinations of the parameters is selected within the parameter uncertainty space. As the emulator is required to predict the model output equally well across the k -dimensional parameter space, the input combinations have to be well-spaced and offer a good coverage. This is ensured by the use of maximin Latin hypercube sampling (Morris and Mitchell, 1995) to select these input combinations. We perform COSMO simulations for these input combinations and use them along with the corresponding outputs to train the emulators (*training data*). We used $15k$ input combinations to train the emulator, with k the number of input parameters, which is 6 in S1, 7 in S2 and 6 in S3. Furthermore, 10 simulations were added to the training datasets of S1 and S3 to increase the quality of the emulator fit. Thus, per Setup, 100 (S1 and S3) or 105 (S2) simulations were run to generate the training data.

The extension of a Gaussian distribution to an infinite number of variables is referred to as a Gaussian process (Rasmussen, 2004). A Gaussian process is defined by a mean function $m(\mathbf{x}) = \mathbf{h}(\mathbf{x})^T \beta$ and a covariance structure $V(\mathbf{x}, \mathbf{x}') = \sigma^2 c(\mathbf{x}, \mathbf{x}')$ where $\mathbf{x} = (x_1, \dots, x_k)$ is a possible input combination, $\mathbf{h}(\mathbf{x})$ contains the regression coefficients for the mean functional form, $c(\mathbf{x}, \mathbf{x}')$ is a correlation function and β and σ^2 are unknown coefficients. The specifications of the mean and the covariance reflect prior beliefs about the form of the emulator. We assume a linear trend for the mean function and use the Matérn correlation structure as it copes better with a slight roughness in the output surface (Rasmussen and Williams, 2006). These choices have been discussed in more detail by Lee et al. (2011), and have since then be used by a number of studies (Johnson et al., 2015; Igel et al., 2018; Wellmann et al., 2018; Glassmeier et al., 2019). Following the Bayesian paradigm, the a priori assumptions are updated using the training data by optimizing the marginal likelihood. The fitted emulator is then given by the resulting posterior specification of the Gaussian process (O'Hagan, 2004, 2006). Once an emulator is constructed, it needs to be validated to ensure an accurate estimation of the model output (Bastos and O'Hagan, 2009). For this, an additional 45 simulations with other input parameter combinations were conducted per setup. When comparing the emulator results to the results of the validation simulations, only a small number of outliers (up to 3) outside the 95% confidence intervals are accepted. In addition, a test for robustness of the choice of the training dataset has been conducted by interchanging the training dataset with parts of the validation data. The validated emulator is then able to predict ~~the~~ (with a certain error as constrained by the validation) the output at all points in the multi-dimensional parameter uncertainty space that were not included in the training set and thus replaces the costly simulations of the NWP model.

3.2 Variance-based sensitivity analysis

Variance-based sensitivity analysis aims to decompose output variance into contributions from the uncertain input parameters. These include both contributions from each individual parameter and contributions from interactions of the parameters. The decomposition of the variance V can be written as (Oakley and O'Hagan, 2004)

$$V = \sum_i V_i + \sum_{i < j} V_{ij} + \dots + V_{1\dots k} \quad (3)$$

assuming independence between the input parameters. V_i are the individual contributions from each parameter, V_{ij} denotes the contribution with respect to the interaction of two parameters, i and j , up to $V_{1\dots k}$ describing the joint interaction of all parameters together. To accomplish this decomposition, we use the extended Fourier amplitude sensitivity test (FAST) by Saltelli et al. (1999) where the k -dimensional parameter space is transformed to 1D Fourier space. Thus, the whole parameter space can be sampled by a monodimensional curve in the Fourier space ~~along all parameters change simultaneously~~. However, as several thousand runs would be necessary to get a space-filling curve, emulators are crucial for the required model output (Oakley and O'Hagan, 2004). A measure for the contribution from each parameter to the output uncertainty is given by the so-called *main effect* $S_i = \frac{V_i}{V}$, which we obtain by normalizing the variance contribution of the parameter V_i with the overall variance V in the output. Thus, the output variance could be reduced by the percentage given by S_i if there was no uncertainty in the input i . Consequently, the difference between the overall variance and the sum of the contributions of the individual parameters describes the amount of variance that arises from interactions of the parameters (*interaction effect*).

4 Sensitivity Analysis for variations of the microphysics (S2)

In the analysis, we consider several output variables ~~which will be described in more detail in this section. These are the hydrometeor masses~~ for which emulators are derived as described above. These output variables, including vertically integrated hydrometeor mass contents, precipitation, diabatic heating rates and the size distribution of surface hail, will be described in more detail in this section. The results of the sensitivity analysis are shown for variations of the microphysical parameters only (S2). Similar analyses for variations of the environmental conditions (S1) have been discussed in Wellmann et al. (2018).

4.1 Hydrometeor ~~masses~~ mass contents and precipitation

The output variables of the model have to be reduced to 0 dimensions in order to be represented by the emulators. We are interested in the variables that are linked to severe weather at the surface (as precipitation maxima and hail), but also in the in-cloud processes causing them, and therefore in the microphysical properties of the cloud. To reduce the dimensionality of the output, the composition of the cloud is described by the vertically integrated mass content of each hydrometeor class that includes cloud water, hail, ice, snow, graupel and rain. The spatial and temporal mean is taken for the considered ~~hydrometeor contents~~ vertically integrated hydrometeor mass contents (all in kg m^{-2}).

The set of considered precipitation variables ~~includes~~ include the amount of hail at the ground per output interval of 15 minutes, the precipitation rate of hail ~~, the accumulated total precipitation and the~~ and the total precipitation ~~rate~~ rate (all in $\text{kg m}^{-2} \text{s}^{-1}$) and the accumulated total precipitation (in kg m^{-2}). Precipitation is analyzed similarly to the hydrometeor masses, but maximum values in space and time are considered instead of mean values. An exception is the amount of hail at the ground ~~where~~ for which both mean and maximum values are analyzed.

The results of the variance-based sensitivity analysis are shown as a bar plot in Fig. 1, where the hydrometeor contents are depicted on the left hand side and precipitation on the right hand side. Each bar represents one output variable, and the different colors denote the contributions from the input parameters to the output uncertainty (*Main Effect*). If there is blank

space above the bar, this means that the first-order main effects are not able to explain all of the output uncertainty and that there are contributions from interactions of the input parameters.

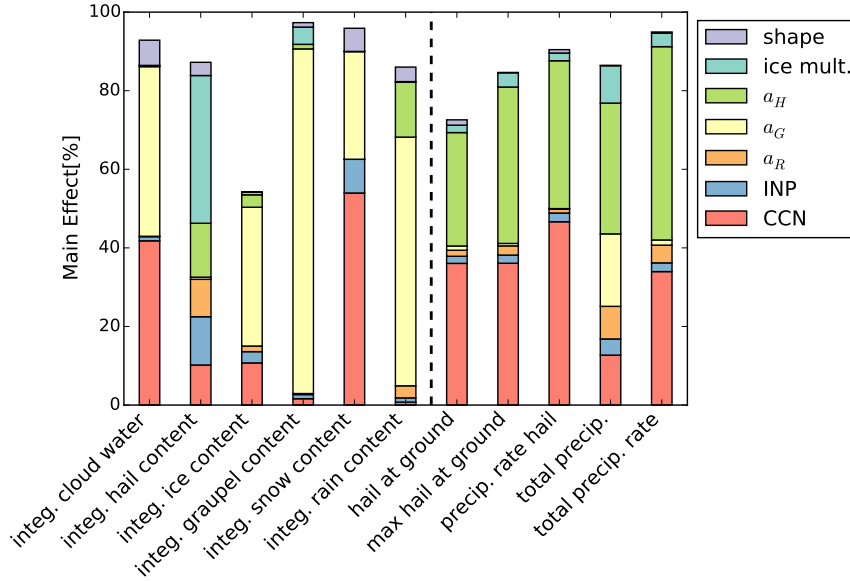


Figure 1. Bar plot of the main effect for vertically integrated hydrometeor ~~masses~~ mass contents (left) and precipitation (right) of cloudy grid points when only microphysical parameters are varied.

Fig. 1 reveals that ~~the fall velocity of graupel modified by the scaling~~ of the investigated parameters, the graupel fall velocity factor a_G is the largest contributor to the output uncertainties of most of the integrated hydrometeor ~~masses~~ mass contents. For example, the uncertainty of the integrated cloud water content could be reduced by 43% and the uncertainty of the integrated graupel content could even be reduced by 88%, if a_G was known exactly. The second most important parameter is the CCN concentration, which contributes especially to the uncertainties of cloud water ~~and~~ (because it determines autoconversion and thus impacts the partitioning between cloud and rain water) and snow content. In contrast, neither a_G nor the CCN concentration are the dominant parameters regarding the integrated hail content. Instead the strength of the ice multiplication is the largest contributor for that output variable (38% of the output uncertainty).

The output uncertainties of the considered precipitation variables are all dominated by contributions from the CCN concentration (13% – 47%) and the fall velocity of hail ~~affected~~ , modified by the scaling factor a_H (29% – 49%). ~~Contributions from the other parameters are only of minor importance.~~ For the maximum total precipitation, the scaling factor for the fall speed of graupel, a_G , is also relevant. This is in line with the expectation that for cases of strong convection, cold phase processes (including riming onto graupel) dominate precipitation formation, as was shown e.g. by Schneider et al. (2019).

4.2 Heating rates

Deep convective clouds usually cover a large area and thus are able to influence the surrounding atmosphere. Furthermore, diabatic processes cause a redistribution of energy such as heating due to condensation and freezing or cooling due to evaporation and melting. To examine how the simulated storm impacts the ~~ambient conditions~~[temperature profile](#), we interpret the vertical profiles of the diabatic heating rates. Joos and Wernli (2011) separate the associated temperature changes into contributions from phase transitions between the different hydrometeors such that it can be described as

$$\frac{\partial T}{\partial t} = \frac{L_v}{c_p} (S_C + S_R) + \frac{L_s}{c_p} (S_I + S_G + S_H + S_S) \quad (4)$$

where L_v and L_s are the latent heat of vaporization and sublimation and c_p is the specific heat capacity of dry air for isobaric processes. The terms S_x specify the conversion processes producing cloud water (C), rain (R), ice (I), graupel (G), hail (H) or snow (S) that include phase transitions and therefore either supply or subtract energy from the surrounding air. Thus, the heating rate $\left. \frac{\partial T}{\partial t} \right|_x$ related to each hydrometeor class x is defined as

$$\left. \frac{\partial T}{\partial t} \right|_x = \frac{\frac{L_{v/s}}{c_p} \frac{L_{v,s}}{c_p}}{\frac{L_{v/s}}{c_p} \frac{L_{v,s}}{c_p}} \cdot S_x \quad (5)$$

where L_v is chosen for transitions between vapor and liquid, L_s for transitions between vapor and ice and $L_s - L_v$ for transitions between liquid and ice. The spatial mean of the heating rates is calculated for each particle class in each layer ~~such that vertical profiles of the heating rates are available~~. The temporal means of these profiles are predicted using separate emulators for each vertical level.

In order to obtain statistically robust results and to minimize the effect of single extreme events, emulators are used to generate 10,000 realizations of the vertical profiles of the heating rates covering the whole parameter space. Subsequently, mean and standard deviation are calculated over all profiles together. [Using this method, we are able to link changes of the total heating rate to the individual hydrometeor classes. Furthermore, the standard deviation is a measure of how much the heating rates react to variations of the input parameters.](#) Fig. 2 shows the domain mean vertical profiles of the heating rates (left), where the shadings denote the standard deviation, and the corresponding main effects for the total heating rate in the considered vertical levels (right). [Simulations with a near-identical model setup were analyzed by Barrett et al. \(2019\), and we refer to the hydrometeor profiles shown in their Fig. 3 and their process rate analysis for the rain water budget to support the interpretation of our results.](#)

Close to the ground the total heating rate is negative because of the cooling caused by evaporation of rain. As there is a strong increase of the heating due to the formation of cloud water, the total heating rate becomes positive above a height of about 1.3 km and reaches its maximum of 5.7 K h^{-1} at $z = 5 \text{ km}$. At higher altitudes, there are ~~smaller~~[additional positive](#) contributions from the formation of graupel and ice. However those are smaller than the contribution from the cloud water such that the total heating rate decreases and is less than 1 K h^{-1} above 10 km. In general, the profiles are quite robust to variations of the input parameters as the standard deviation is rather small (max. 20% and on average less than 5% of the absolute value for the total heating rate). The bar plot of the main effect (Fig. 2, right) reveals that the fall velocity of graupel (a_G) is the most

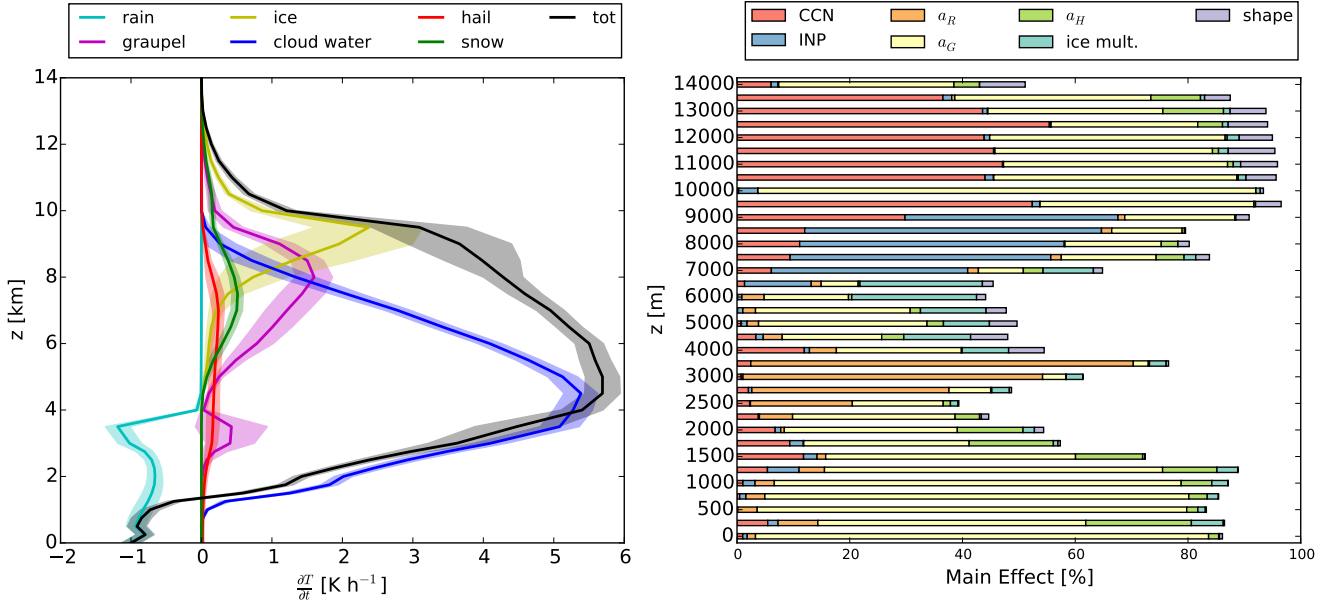


Figure 2. Left: Vertical profiles of the mean diabatic heating rates by each hydrometeor class and the mean total diabatic heating rate for variations of the microphysics. The shaded areas denote the standard deviation. Right: Bar plot of the corresponding main effect for the total heating rate. Note the different axis tick spacing below and above 3 km.

important contributor to the output uncertainty of the total heating rate. In the height between 3 km and 4 km there are also major contributions from the fall velocity of rain (a_R). CCN contributes only modestly to uncertainty at these levels, although the heating rate by condensation is very strong here. This is probably linked to the fact that a saturation adjustment scheme is used for cloud condensation, which is thus insensitive to droplet number and size. Below 2.5 km, coinciding with the largest cooling due to the evaporation of rain-, a_G is again the major driver of uncertainty. As shown by Barrett et al. (2019), roughly half of the surface rain in this model setup originates from cold rain processes involving riming. Therefore here the graupel (and also hail) fall speed parameters contribute substantially to the uncertainty of the latent heating rate at levels below 2 km, although there is no graupel present at these altitudes.

Corresponding to the heating by the formation of ice between 7 km and 10 km, there are large contributions to the output uncertainty from the INP concentration in this height. Above, the output uncertainty of the total heating rate is dominated by the CCN concentration and the fall velocity of graupel.

Using this method, we are able to link changes of the total heating rate to the individual hydrometeors. This is probably linked to the indirect effect of CCN and riming efficiency on the amount of supercooled water transported to the homogeneous freezing level. Furthermore, the standard deviation is a measure of how much the heating rates react to variations of graupel is produced at these levels in our model as a result of the input parameters freezing of rain drops, and the graupel fall speed factor thus impacts the gravitational sink of the (small) graupel particles present at these altitudes.

4.3 Size distribution of surface hail

The size distribution of hailstones reaching the ground is of interest regarding the damage potential of hail events. For the size distributions of hydrometeors, a generalized Γ -distribution is implemented in the two-moment scheme of Seifert and Beheng (2006a):

$$5 \quad \frac{dN}{dx} = Ax^\nu \exp(-\lambda x^\mu) \quad (6)$$

- where N is the number [densityconcentration](#), x represents the particle mass and ν and μ are parameters of the Γ -distribution (cf. section 2.2). The coefficients A and λ are given by gamma distributions and the number and mass density, respectively (Seifert and Beheng, 2006a). To obtain a measure for the number of particles per diameter, the term $\frac{dN}{dx}$ is transformed to $\frac{dN}{dD}$ by a conversion from mass x to particle diameter D . The spatio-temporal mean of the size distribution of surface hail is
- 10 represented by emulators of the number [densityconcentration](#) at ten fixed diameters. To constrain the parameter space and thus limiting the regimes describing different environmental or microphysical conditions to a feasible amount, each of the uncertain input parameters is assigned two discrete values where both a lower and a higher value are chosen (Table 3). These two values are denoted by "-" and "+". [Hereby, the outer bounds of the environmental parameters \$F_{shear}\$ and \$\theta_0\$ from S1 are taken as "-" and "+", as they are already limited to the typical range of forecast errors. For all other parameters, the lower and higher values](#)
- 15 [are subjectively chosen to be representative, but not extreme, and encompass therefore a smaller range than examined in S1, S2 and S3.](#) The considered regimes emerge from all possible combinations of these parameter values.

Table 3. Input values representing both lower and higher values of the parameter ranges used to analyze the size distribution of hail. Parameters marked with * are part of setup 1, ° relates to setup 2 and † to setup 3.

input	lower value (-)	higher value (+)	units
CCN concentration ^{*†}	500	3000	cm ⁻³
IN concentration ^{*†}	0.1	10	scaling factor
wind shear (F_{shear}) ^{*†}	0.5 0.3333	1.0 0.6666	scaling factor
potential temperature θ_0 ^{*†}	299	301	K
temperature perturbation ΔT (WB) [*]	2	5	K
radius of warm bubble R_{hor} [*]	7	13	km
fall velocity of rain a_R [°]	0.5	1.5	scaling factor
fall velocity of graupel a_G ^{°†}	0.5	1.5	scaling factor
fall velocity of hail a_H ^{°†}	0.8	1.2	scaling factor
ice multiplication [°]	$0.7 \cdot 10^8$	$6.3 \cdot 10^8$	kg ⁻¹
shape parameter [°]	2	6	-

The size distribution of surface hail is simulated using the emulators for all possible combinations of the input parameters for each setup. Fig. 3 (left) shows the mean size distributions of surface hail from all combinations and the corresponding main effect for variations of the microphysics only using S2. The size distributions with the lowest and highest number concentrations are marked in a different color such that a separation into three groups is visible.

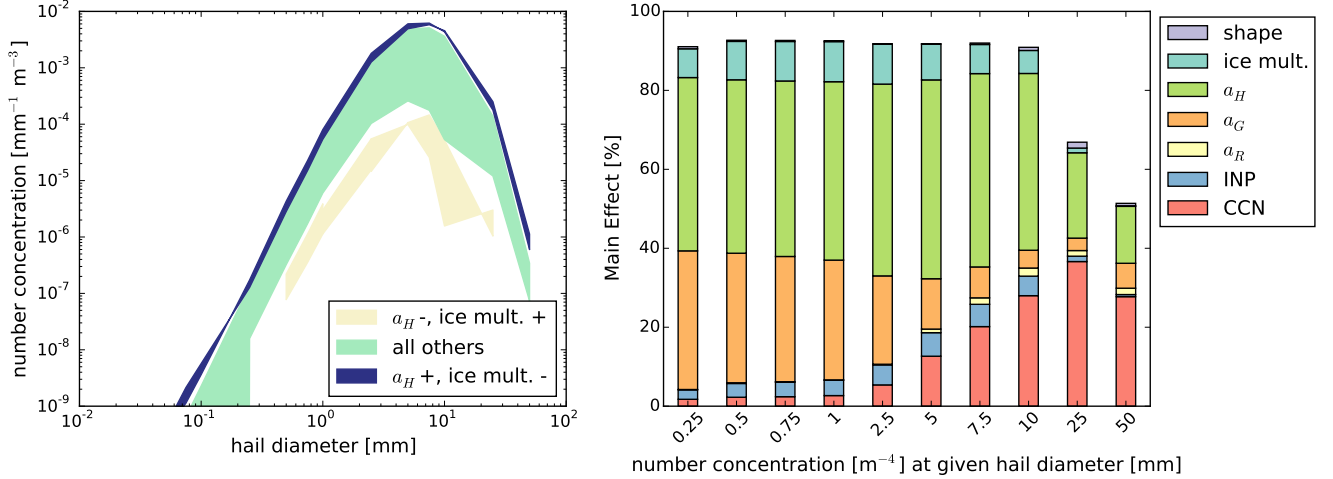


Figure 3. Left: Size distributions of hail at $z = 0$ m for variations of the microphysics. The shading illustrates regimes of the size distributions controlled by the fall velocity of hail. Right: Bar plot of the corresponding main effect for the number concentration of the size distribution of surface hail. Here, hail is defined according to the hydrometeor class in COSMO.

- 5 The distributions in the two groups with either very low or very high number concentrations share common features regarding the combination of the input parameters. The lowest number concentrations of hail (over the entire size distribution) are found for regimes with a low value of the fall velocity of hail and a high value for the strength of the ice multiplication. These distributions show maximum number concentrations of $0.06 - 0.15 \text{ mm}^{-1} \text{m}^{-3}$ at a diameter of 7.5 mm. In contrast, the highest concentrations of $6.38 \text{ mm}^{-1} \text{m}^{-3}$ at a diameter of 5 mm are simulated for a high value of the fall velocity of hail.
- 10 Thus, the fall velocity of hail and the strength of the ice multiplication are the most important controlling parameters of the size distribution.

- The corresponding plot of the main effect (Fig. 3, right) confirms the impact of the fall velocity of hail (a_H) and the strength of the ice multiplication as the sum of their contributions together to be responsible for large parts of the output uncertainty of the number concentration at the considered diameters all considered diameters except at $D < 25$ mm. These two parameters
- 15 contribute more than 50% to the output uncertainty for most diameters. Only at these diameters. At the largest considered diameters their impact is reduced due to increased contributions, an increased contribution from the CCN concentration -comes into play, while smaller diameters are significantly impacted by the graupel fall speed. This may be linked to the two formation pathways of hail in COSMO, namely through freezing of rain (of which the size is impacted by the CCN concentration) and through riming of graupel.

5 Comparison of the three setups

In the next step we analyze the impact of the input parameters on the uncertainty of the output variables of hydrometeor **masses** mass contents and precipitation by comparing the results for the three different setups with changes of 1) environmental conditions only, 2) microphysical parameters only and 3) both environmental conditions and microphysical parameters (S1 - S3, see sections 2.1-2.3). If the results of S3 resemble more those of S1, then the impact of the parameters describing the environmental conditions is more dominant. Correspondingly, the microphysical parameters are more dominant if S3 resembles S2.

5.1 Hydrometeor **masses** mass contents and precipitation

To compare the main effects of the three emulator studies, the results are combined in a bubble plot (Fig. 4) where the contribution of each considered input parameter to the output uncertainty is represented by the size of a circle. The circles of the different sets of input parameters are placed in columns next to each other labeled by S1, S2 and S3.

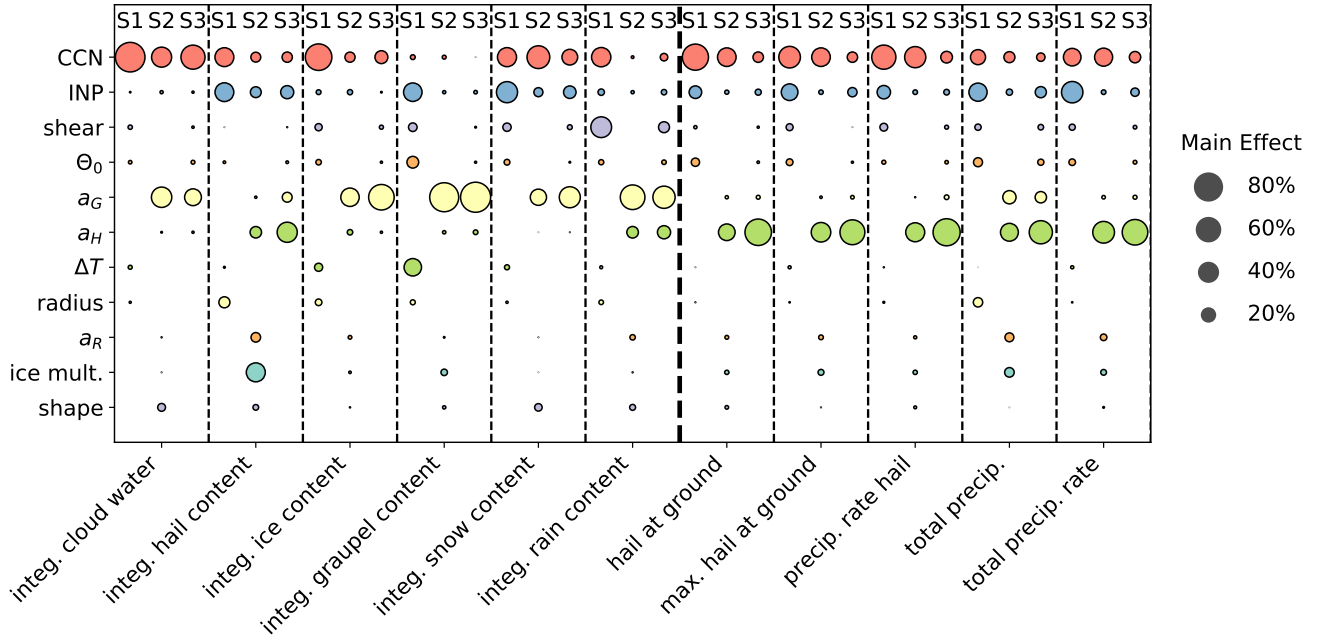


Figure 4. Bubble chart of the contributions from all input parameters of the different emulator studies to the output uncertainty of cloud and precipitation variables. The main effects of all input parameters given on the y-axis are depicted as circles where the size corresponds to the value of the main effect. The different columns labeled with S1, S2 and S3 represent the results of each emulator study (S1: environmental conditions, S2: microphysics, S3: both environmental conditions and microphysics; see sections 2.1-2.3).

The CCN **and** INP (100 to 4000 cm⁻³) and INP (factor 0.01 to 10) concentrations are changed within the same range in all setups such that the results from three separate ensembles can be compared. The contributions from the CCN concentration

variations to the output uncertainty of the integrated cloud water and the integrated snow content in S3 are similar to those in S1. For the other variables, the contribution in S3 is rather comparable to the contribution in S2, while the contribution in S1 is larger. This trend is also consistent for the precipitation output. Here, the contribution from the CCN concentration uncertainty decreases from S1 to S3 such that the results of S3 are closer to those of S2.

5 The contributions from the INP concentration variations are mostly larger in S1 than in S2 for both integrated hydrometeor ~~masses~~mass contents and precipitation. The main effects in S3 are a combination of S1 and S2, but the results are closer to those of S2 than to those of S1. Thus, the main effect of the INP concentration is smaller if other microphysical parameters are used as input, possibly because other ice phase processes (secondary ice formation, riming) can suppress the sensitivity of a cloud to primary ice formation.

10 The behavior of the wind shear is quite consistent for the considered output variables. ~~The contribution from the wind shear~~ Its contribution is in general ~~smaller in~~small, except if the integrated rain water content is the target output variable. It is always larger in S1 than in S3~~which means~~, meaning that the wind shear has a larger impact on the output uncertainty, if only the environmental conditions are varied. Similarly, the (already small) impact of θ_0 is reduced in S3; compared to the effect of cloud microphysics its impact is diminished.

15 The main effect of the fall velocity of graupel is larger for the cloud variables than for precipitation. Furthermore, in most of the cases the fall velocity of graupel has a similar effect on the output uncertainty in S3, such that a_G is still important in cases when parameters describing the environmental conditions are also part of the input parameters.

When looking at the hydrometeor ~~masses~~mass contents, the contribution from the fall velocity of hail to the output uncertainty is negligible except for the integrated hail and rain contents. However, it is the largest contributor to the uncertainty of the precipitation variables, presumably reflecting that hail itself and melted hail constitutes a major part of the total precipitation. Here, its impact is larger in S3 compared to S2 for all variables so that its importance expands when also environmental conditions are involved.

20 The ~~remaining input parameters~~other input parameters (ΔT , radius, a_B , the ice multiplication factor and the shape parameter) are only used ~~once~~in one of the setups so that a direct comparison of different setups is not possible. They are included in Fig. 4 for completeness.

Summarizing, we find that the uncertainty of the integrated hydrometeor ~~masses~~mass contents and the precipitation mainly emerges from the uncertainty of the microphysics, in particular from the fall velocity of graupel for the hydrometeor ~~masses~~contents and from the fall velocity of hail for precipitation. The contributions from the parameters characterizing the environmental conditions are rather small in S3.

30 In the literature, the focus of sensitivity studies is mainly on the effect of CCN concentrations on clouds, but there are also studies examining the effect of other parameters such as wind shear, temperature perturbation or shape parameter of the cloud droplet size distribution. For example, Brooks (1992) analyses the effect of the warm bubble characteristics on deep convection. He finds that variations of ΔT cause only minor differences in precipitation, and the updrafts are strongest for medium horizontal radii of the bubble. The effect of the horizontal radius on the precipitation is not mentioned. Our results are in good agreement with the findings of this work. Both ΔT and the radius of the bubble hardly contribute to the output

uncertainty of the precipitation variables, and also the impact on the hydrometeor ~~masses~~contents is rather small (Fig. 4). Regarding vertical wind shear, Dennis and Kumjian (2017) observe a significant effect of the wind shear on the hail production. Here, the contribution of the wind shear to the output uncertainties of hail variables is rather small. However, it is expected to see a larger impact when the wind shear does not have to compete with the more dominant effects of other parameters;

5 ~~comparable to Dennis and Kumjian (2017)~~. Furthermore, in our study the parameter range of the wind shear is chosen to reflect typical forecast errors and not a broad range of atmospheric conditions. ~~Therefore, its impact is limited~~ This results in a smaller impact of the wind shear variation compared to the setup of Dennis and Kumjian (2017).

The impact of CAPE on deep convection is analyzed by Storer et al. (2010). In their study, the ~~cloud generally reacts updraft strength and the total accumulated precipitation are very sensitive~~ to changes in CAPE, while ~~in particular~~ the integrated

10 amount of cloud water does not depend strongly on CAPE. Furthermore, they conclude that the impacts of CAPE and CCN concentration ~~are~~can be comparable. Fig. 4 confirms that the contribution from θ_0 to the uncertainty of the integrated cloud water in S1 and S3 is not dominant. Yet, in total the effect of the two parameters is not similar as the contributions from the CCN concentration are clearly larger. This is caused by the chosen parameter range of θ_0 limited to typical forecast errors and thus not comparable to the parameter range assumed by Storer et al. (2010). ~~Igel and van den Heever (2017b)~~ examine

15 shallow cumulus clouds for different shape parameters of the cloud droplet size distribution and notice an effect on the droplet concentration, but not on the mass mixing ratios. The results of our study agree with their work, as the shape parameter is only of minor importance for the integrated cloud variables. With respect to the ~~aerosol effect~~impact of CCN variation, our findings are in good qualitative agreement with the works of Fan et al. (2013) and Yang et al. (2017), for instance. Fan et al. (2013) ~~observe changes of 25% of the anvil expansion find an increase of approximately 30% of the upper tropospheric cloud cover~~

20 due to changes of the CCN concentration ~~and from 280 to 1680 cm⁻³ (which is smaller than our parameter range)~~. Yang et al. (2017) find clear differences in the vertically integrated condensate mixing ratio, such as an increase of ice from 6 to 18 g kg⁻¹, for increasing CCN from 300 to 5000 cm⁻³ (similar to our parameter range). This is comparable to the significant influence of the CCN concentration on the output uncertainty of the hydrometeor contents found here.

5.2 Heating rates

25 In this study, the diagnostics of diabatic heating rates are implemented similar to Joos and Wernli (2011) (see section 4.2). The mean profile and the standard deviation of 10,000 randomly generated realizations are illustrated in Fig. 5.

There is diabatic cooling of about -1 K h^{-1} near the ground in all setups due to the evaporation of rain. Between 1.25 and 1.5 km height the rate becomes positive and increases until its maximum is reached at a height of 4.5 km. The maximum values of the heating rate vary between 5.7 K h^{-1} for setup 2 and 5.9 K h^{-1} for S1 and S3. Above, the total heating rate decreases

30 slowly up to 8 km. Between 8 and 10 km there is a stronger decrease of the heating rate such that its value is close to 0 K h^{-1} at higher altitudes.

Up to 4 km above the ground, the profiles of the mean heating rates are almost identical for the three considered setups. Also the standard deviations are small and almost negligible which means that near the ground the total heating rate is rather insensitive to changes of the input parameters, both environmental conditions and microphysical parameters. However, above

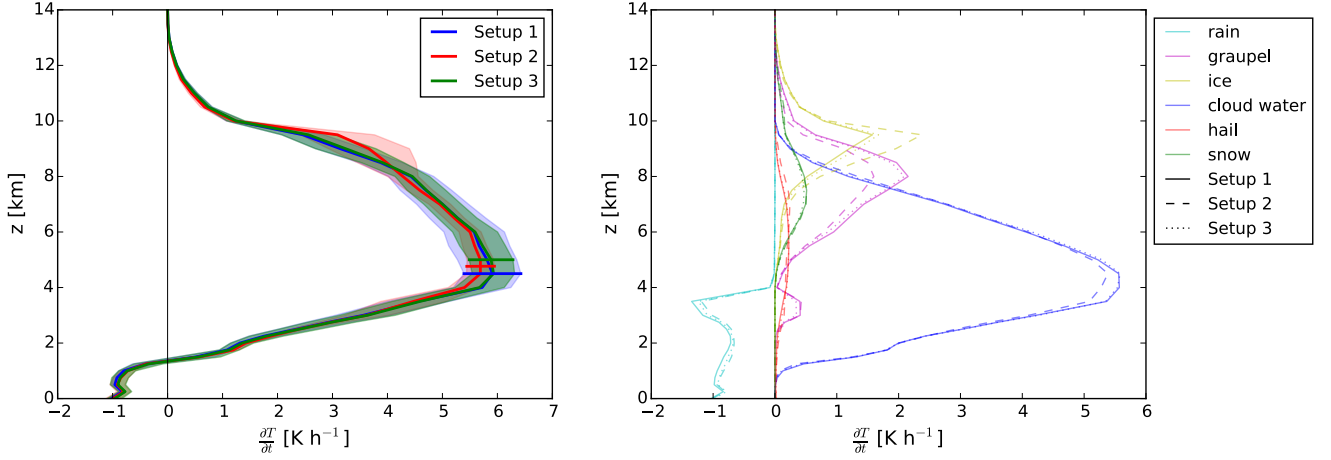


Figure 5. Vertical profiles of the mean total diabatic heating rate (left) and the mean heating rates for each hydrometeor class (right). The shaded areas left denote the standard deviation, which is also indicated by a horizontal bar at one selected altitude.

4 km the profiles of S1 and S2 deviate from each other. The maximum of the total heating rate reached in S1 is slightly higher and the standard deviation enlarges to approximately 1 K h^{-1} while the standard deviation of S2 remains at values of 0.5 K h^{-1} . The difference of the mean profile can be attributed to different contributions from the formation of cloud water that is smaller in S2 (Fig. 5, right). Here, the profile of S3 shows higher values and thus resembles the profile of S1. Another slight deviation of the profiles of S1 and S2 occurs in a height of $8 - 10 \text{ km}$. At this point, the profile of S2 shows values that are up to 0.6 K h^{-1} larger than those of S1. Moreover, the standard deviation of S2 is increased to 0.7 K h^{-1} at these altitudes. This increase of the total heating rate in S2 is caused by an enhanced contribution from the formation of cloud ice at these altitudes as can be seen in Fig. 5, right. At this height, the profile of S3 is almost identical to that of S1. Above 10 km the heating rates of all setups are close to each other showing only limited effects of the variations of the input parameters. Furthermore, the standard deviation of the profile of S3 is comparable to the standard deviation of S1, yet it is reduced by about 0.2 K h^{-1} in the middle troposphere. Therefore, variations of the environmental conditions have a larger impact on the total heating rate than variations of microphysical parameters. This dominance of the environmental conditions is also obvious in Fig. 5 (right). Near the ground, the total heating rate is determined by the cooling due to evaporation of rain, while in the mid-troposphere the largest contributions stems from the formation of cloud water mainly caused by the use of saturation adjustment in the microphysics scheme. At higher altitudes the hydrometeors of the ice phase, especially graupel and cloud ice, contribute the most to the total heating rate. For all hydrometeors, the profiles of S3 (dotted) are close to those of S1 (solid), whereas the profiles of S2 (dashed) differ. Thus, the environmental conditions dominate the impact on the vertical profiles of the heating rates for both the total heating rate and the individual heating rate contributions from each hydrometeor class.

~~A remarkable feature in all setups is the large contribution of output uncertainty from the formation of cloud water mainly caused by saturation adjustment. Hence, the diabatic heating related to cloud water~~ Condensation of cloud water, which is

a substantial contributor to the total heating rate in the lower and middle troposphere, is parameterized via a saturation adjustment scheme in our model. Nevertheless, it yields a large contribution to output uncertainty of the diabatic heating in all three setups. This effect might be even larger if a time-dependent treatment of condensation was used. Wang et al. (2013), for example, find that there are discrepancies of the results between models including saturation adjustment and those explicitly calculating diffusional growth of cloud droplets. These differences are mainly characterized by an overestimation of the condensation in the lower troposphere affecting the diabatic heating rates. In addition, Lebo et al. (2012) also state that saturation adjustment artificially increases condensation. This increase appears to be quite strong as it is also represented by the emulators. Therefore, modified results of the sensitivity studies are expected for the heating rates, if the saturation adjustment is replaced by more realistic calculations. However, Dennis and Kumjian (2017) specify in their work that process rates are not an essential factor causing discrepancies in the formation of hail for different model setups.

5.3 Size distribution of surface hail

In this section, we analyze the impact of the different input variations of environmental conditions and microphysical parameters on the size distribution of surface hail. As described in section 4.3, each input parameter is assigned two discrete values and the size distribution is predicted by the emulators for all possible combinations. In Fig. 6 both the distributions with the lowest and highest number concentrations are illustrated for each setup. Consequently, all other distributions are found in-between which is indicated by the shading. The combinations of the parameters producing the extreme distributions, and thus the controlling input parameters of the size distributions, are given in the legend.

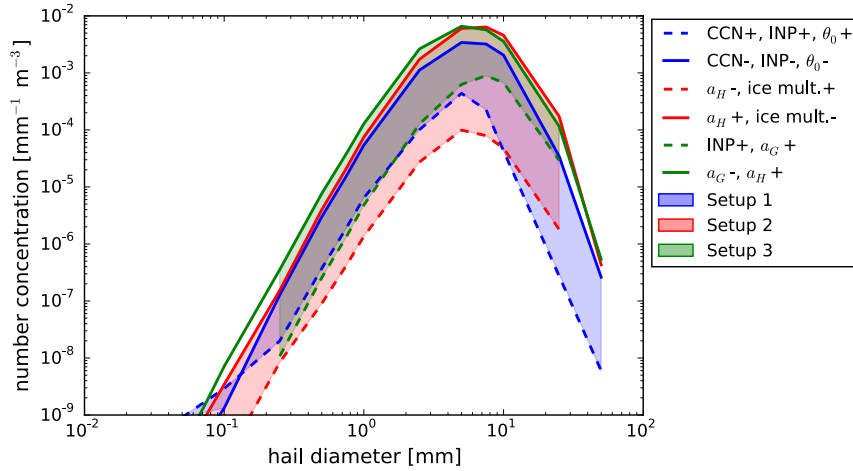


Figure 6. Size distributions of hail at $z = 0$ m. The shading illustrates the number concentrations covered by all possible combinations of input parameters for each setup. The solid lines indicate the distributions with the highest number concentration while the dashed line represents the distributions with the lowest number concentration of each setup. The corresponding combination of controlling input parameters is given in the legend.

For S1, the size distribution with the lowest number concentration (dashed blue line) has its maximum of $0.44 \times 10^{-4} \text{ mm}^{-1} \text{ m}^{-3}$ at a hail diameter of 5 mm. The maximum of the distribution with the highest number concentration (continuous blue line) is also found at the same diameter but with a number concentration of $3.43 \times 10^{-3} \text{ mm}^{-1} \text{ m}^{-3}$. For this setup ~~regarding~~ (in which the environmental conditions are modified), the controlling parameters are the CCN and INP concentrations and θ_0 ~~where low number concentrations~~. Low number concentrations of hail arise for higher values of these parameters and high number concentrations of hail for lower values.

The maximum of the size distribution with low number concentrations of S2 (dashed red line) is only a fourth of the concentration of S1 while for the distributions with the highest number concentration (continuous red line) it is almost twice the amount. Hence, the spread of all distributions is larger.

For S2, the low (dashed red line) and high (continuous red line) hail size distributions are smaller and larger, respectively, than those for S1, leading to a larger spread in the distributions. The fall velocity of hail and the strength of the ice multiplication are the two microphysical parameters that mainly determine the number concentration of surface hail. Low number concentrations are found for a low value of the fall velocity of hail combined with a high value for the strength of the ice multiplication and vice versa.

When both the environmental conditions and the microphysics are perturbed, the amount of hailstones approximately double compared to S1 for the distribution with the lowest number concentration. The distribution with the highest number concentration has similar concentrations as S2. The combination of high INP concentrations and high fall velocities of graupel produce a low number concentration of surface hail whereas low fall velocities of graupel ~~and~~ (presumably resulting in more time for riming of graupel and growth to hail) and high fall velocities of hail (possibly by leaving less time for melting below the cloud) lead to high number concentrations.

Comparing the results of the different setups, the distribution with the lowest number concentration of S3 is similar to the corresponding distribution of S1. Especially for small diameters the two distributions show similar number concentrations. In contrast, the distribution with the highest number concentration of S3 (continuous green line) resembles the distribution of S2 as high number concentrations are reached that are comparable to S2. Furthermore, the spread between the distribution with the lowest and the highest number concentration is smaller in S1 and larger in S2 such that the spread of S3 is situated in-between. Moreover, the controlling parameters identified in S3 include parameters from both environmental conditions ~~and microphysics. Although the INP concentration is part of the input parameters of all three setups, its impact on the size distribution in S3 is attributed to the environmental conditions (S1) as it was a controlling parameter in S1 only~~ (INP) and microphysics (a_G, a_H).

Summarizing, the environmental conditions and the microphysical parameters (with the spread of input parameters chosen in this study) have a comparable impact on the size distribution of surface hail. While the microphysical input parameters mainly determine the maximum number concentration, the environmental conditions substantially influence the minimum number concentration. In general, microphysical input parameters cause a larger spread of the number concentrations of surface hail than the inputs related to environmental conditions.

The results above should not be regarded as definite number concentrations of surface hail, as a bulk model is used here, and several studies note that the representation of hydrometeor sizes is more accurate in bin schemes (Dennis and Kumjian, 2017; Lee et al., 2008). To approach this issue, Loftus and Cotton (2014) introduce a modified microphysics setup where a three-moment scheme is implemented for an improved prediction of hail. They find that increasing the CCN concentration induces an increase of the hail sizes, but a decrease of the number of hailstones. The CCN concentration is identified as the controlling parameter of the size distribution in this study as well, but not for all considered setups. Because Loftus and Cotton (2014) investigated the effect of the CCN concentration only, it is possible that in our study the effect of the CCN concentration is covered by larger impacts of other input parameters such as the fall velocity of hail. Thus, the classification of the controlling parameters of the size distribution of hail is assumed to be appropriate although a bulk microphysics scheme is used. Further studies similar to Loftus and Cotton (2014), incorporating modifications of the microphysics scheme and the variation of not only one but several parameters, are necessary to confirm these findings.

6 Summary & Conclusions

In our study, we have investigated how changes in the environmental conditions and cloud microphysics impact deep convection with a focus on the integrated hydrometeor ~~masses~~mass contents, precipitation, diabatic heating rates and the hail size spectrum.

The COSMO model was used to simulate deep convective clouds in an idealized setup, where convection was triggered by an artificial warm bubble. This rather simple setup was required to allow a large number of simulations in which environmental conditions and microphysical parameters are modified. The straightforward approach for analyzing the sensitivity of the model output to changes in the input parameters is to vary a chosen parameter in a given range, while the other parameters are kept constant. However, instead of this one-at-a-time analysis, we employed statistical emulation and variance-based sensitivity analysis where the contributions of the input parameters to the uncertainty of the output are quantified. The emulator approach offers a convenient tool for the identification of relevant parameters without the requirement of running a large number of extensive model simulations. COSMO simulations were used to train the emulators, while the variance-based sensitivity was based on the predictions from the emulators allowing for an identification of not only the impact of each parameter independently, but also their interactions which cannot be captured by one-at-a-time analyses. In total, we evaluated three sets of input parameters. First, a set describing environmental conditions such as potential temperature and vertical wind shear was used. Note that the range of variation of these parameters is designed to mimic typical forecast errors and is therefore smaller than in earlier studies, which have encompassed a wider range of possible conditions. The second set of input parameters focused on cloud microphysics consisting of parameters such as the shape parameter of the cloud droplet size distribution or the fall velocity of hydrometeors. The third set combined influential parameters of both environmental conditions and microphysics.

For all sets of input parameters, the integrated hydrometeor contents, precipitation, size distribution of surface hail and diabatic heating rates were examined with respect to output uncertainty or response to variations of the input.

The analysis of the integrated hydrometeor ~~masses~~contents reveals that the CCN concentration is an important parameter

contributing to the output uncertainty if only the environmental conditions are varied, whereas the fall velocity of graupel provides a large contribution if only microphysical parameters are varied. These parameters are crucial for the efficiency of warm and cold rain formation, respectively. The decomposition of the output variance given variations of both environmental and microphysical parameters is similar to variations of the microphysical parameters only, implying that regarding the integrated hydrometeor ~~masses~~contents, the uncertainty in the microphysical parameters is more dominant in causing uncertainty in the output. Similarly, the CCN and INP concentrations are relevant parameters for the uncertainty of the precipitation output when environmental conditions are considered, while ~~these are~~ the CCN concentration and the fall velocity of hail dominate when microphysical parameters are analyzed. The study combining both sets of input parameters shows a large contribution ~~from~~ by the fall velocity of graupel to the output uncertainty of the hydrometeor loads, and by the fall velocity of hail to the output uncertainty of the precipitation variables. Consequently, variations of the microphysical parameters are the prevailing source of uncertainty of the integrated hydrometeor ~~masses~~contents and precipitation compared to variations of the environmental conditions.

We analyzed the variability of the vertical profiles of the diabatic heating rates by using emulators to predict the profiles of 10,000 randomly generated realizations covering the whole parameter space. The mean profiles for the three sets are almost identical~~and the variability is comparable for variations of environmental conditions only and the combined study whereas the mean profile deviates in~~, with the exception of a deviation of the set with variations in microphysical parameters in the middle and upper troposphere~~for variations of the microphysics~~. The variability is similar for the set with variations of environmental conditions only and the set with combined microphysical and environmental changes. The good agreement between the results of these two sets of input parameters is also confirmed by the component-wise analysis of the heating rates where the contribution from each hydrometeor class to the total heating rate is considered separately. Thus, comparing the impact of environmental conditions and the microphysics on the diabatic heating rates, the effect of the environmental conditions is ~~more~~ dominant. This is in contrast to the result of the integrated hydrometeor ~~masses~~contents and precipitation where the impact of the microphysical parameters is prevalent.

We have assigned two discrete values to each of the input parameters and then used the emulators to predict the hail size distribution for all possible combinations of the input parameters to understand how the surface hail is affected by variations of the environmental conditions and the microphysics. The parameters controlling the size distribution are the CCN concentration, the INP concentration and the vertical temperature profile for variations of the environmental conditions and the fall velocity of hail and the strength of the ice multiplication for variations of the microphysics. The controlling parameters of the combined input parameters are the INP concentration and the fall velocities of graupel and hail, ~~hence a combination of parameters describing environmental conditions and microphysical parameters~~. The range of number concentrations in which the size distributions are found in this combined set is a compromise of the two sets considering environment and microphysics separately where the distribution with the lowest number concentration is close to the results for variations of the environmental conditions and the distribution with the highest number concentration is close to the results for variations of the model

microphysics. Accordingly, both the environmental conditions and the microphysics affect the size distribution of surface hail comparably.

In conclusion, the aim of this work was to identify the sources of forecast uncertainty and to determine whether the variation of the environmental conditions or the variation of the microphysical parameters leads to larger model output uncertainty. It can be expected that our results (in particular regarding the microphysical parameters) depend to some extent on the microphysics scheme of our model. However, the overarching aim of this study was not to emphasize the impact of a specific parameter, but to quantify the relevance of environmental versus microphysical uncertainty in general. We expect that these results are less dependent on the microphysics scheme. In addition, future studies should address how far the results of our idealized simulations are transferable to real cases. For our choices of input parameter ranges, the impact of the environmental conditions versus cloud microphysics depends on the output of interest: The uncertainty in the output of the integrated hydrometeor ~~masses~~contents and the precipitation is affected more by variations of the microphysics, while variations of the environmental conditions cause more uncertainty in the prediction of the vertical profiles of the diabatic heating rates. Further, a comparable impact of environmental conditions and microphysics on the size distribution of surface hail is found. Therefore, depending on the parameter of interest, the forecast uncertainty could be reduced by either an improved observational network and data assimilation providing a more accurate description of the environmental conditions or a revised microphysics scheme, in particular a revised parameterization of the fall velocity of graupel and hail.

Data availability. The processed training data sets and the emulators are published via the open access institutional repository KITopen (doi:10.5445/IR/1000099232). The full model simulations are available upon request.

20 **Appendix A: Numerical values**

Author contributions. JJ and KC provided the code for the emulator approach. CW conducted the analysis and wrote the original draft of the paper with contributions from the co-authors. CH conceptualized the project together with MK and BV, and edited the revised manuscript. CH, AB, MK and BV contributed to the discussion and interpretation of the results.

Competing interests. The authors declare that they have no conflict of interest.

25 *Acknowledgements.* The research leading to these results has been done within the project “Microphysical uncertainties in deep convective clouds and their implications for data assimilation” of the Transregional Collaborative Research Center SFB / TRR 165 “Waves to Weather”

funded by the German Science Foundation (DFG). ~~This work was~~ JJ and KC were supported by the Natural Environment Research Council ACID-PRUF project under grant NE/I020059/1. The simulations were performed on the computational resource ForHLR I funded by the Ministry of Science, Research and the Arts Baden-Württemberg and DFG. Furthermore, we thank Felix Fundel from Deutscher Wetterdienst for providing data on the prediction errors of the COSMO model.

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Table A1. Numerical values represented by the circles in Fig. 4 for the integrated hydrometeor contents. All values are given in %.

	integ. cloud water			integ. hail content			integ. ice content			integ. graupel content			integ. snow content			integ. rain content		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
CCN	91.2	41.8	60.3	37.2	10.2	11.0	73.4	10.7	17.3	2.4	1.6	0.006	37.9	54.0	25.8	38.9	0.7	5.9
INP	0.2	1.1	0.5	36.8	12.3	17.9	2.4	2.9	0.3	35.7	1.1	1.3	46.4	8.6	16.4	4.3	1.1	3.1
shear	2.0	-	0.6	0.01	-	0.09	5.4	-	1.7	7.7	-	0.3	7.2	-	2.5	44.9	-	12.5
θ_0	1.3	-	1.6	0.7	-	0.8	3.1	-	0.5	14.4	-	0.5	3.5	-	0.3	2.8	-	2.1
a_G	-	43.2	29.4	-	0.5	10.1	-	35.3	67.9	-	87.7	94.3	-	27.4	46.1	-	63.3	51.4
a_H	-	0.3	0.5	-	13.7	42.3	-	3.2	0.5	-	1.2	2.3	-	0.005	0.04	-	14.0	18.1
ΔT	1.7	-	-	0.4	-	-	6.9	-	-	31.7	-	-	2.7	-	-	0.9	-	-
radius	0.5	-	-	12.7	-	-	4.6	-	-	2.6	-	-	0.5	-	-	2.2	-	-
a_B	-	0.1	-	-	9.5	-	-	1.4	-	-	0.3	-	-	0.02	-	-	3.1	-
ice mult.	-	0.003	-	-	37.6	-	-	0.6	-	-	4.4	-	-	0.008	-	-	0.09	-
shape	-	6.4	-	-	3.4	-	-	0.1	-	-	1.1	-	-	5.8	-	-	3.7	-

Table A2. Numerical values represented by the circles in Fig. 4 for the precipitation variables. All values are given in %.

	hail at ground			max. hail at ground			precip. rate hail			total precip.			total precip. rate		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
CCN	71.2	36.1	11.4	48.6	36.1	11.2	60.8	46.6	14.2	23.7	12.7	7.4	32.2	34.0	13.5
INP	16.5	1.8	3.8	29.0	2.1	9.0	18.8	2.2	3.4	34.5	4.1	13.0	47.9	2.2	7.3
shear	1.1	-	0.5	5.1	-	0.008	6.4	-	1.6	4.1	-	3.2	4.0	-	1.4
θ_0	7.2	-	0.7	4.8	-	0.5	1.7	-	1.3	8.5	-	4.0	4.5	-	1.5
a_G	-	1.0	1.6	-	0.6	1.3	-	0.1	2.3	-	18.4	13.5	-	1.3	1.7
a_H	-	28.9	73.0	-	39.8	64.5	-	37.5	76.5	-	33.3	56.0	-	49.2	68.2
ΔT	0.01	-	-	1.0	-	-	0.1	-	-	0.002	-	-	1.0	-	-
radius	0.1	-	-	0.2	-	-	0.4	-	-	9.2	-	-	0.2	-	-
a_B	-	1.5	-	-	2.3	-	-	1.0	-	-	8.3	-	-	4.5	-
ice mult.	-	1.9	-	-	3.7	-	-	2.0	-	-	9.5	-	-	3.4	-
shape	-	1.4	-	-	0.05	-	-	0.9	-	-	0.005	-	-	0.3	-