



Impacts of combined microphysical and land-surface uncertainties on convective clouds and precipitation in different weather regimes

Christian Barthlott¹, Amirmahdi Zarboo¹, Takumi Matsunobu², and Christian Keil²

¹Institute of Meteorology and Climate Research – Department Troposphere (IMK-TRO),
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

²Meteorologisches Institut, Ludwig-Maximilians-Universität, Munich, Germany

Correspondence: Christian Barthlott (christian.barthlott@kit.edu)

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Abstract. To reduce the underdispersion of precipitation in convective-scale ensemble prediction systems, we investigate the relevance of microphysical and land-surface uncertainties for convective-scale predictability. We use three different initial soil moisture fields and study the response of convective precipitation to varying cloud condensation nuclei (CCN) concentrations and different shape parameters of the cloud droplet size distribution (CDSD) by applying a novel combined-perturbation strategy. Using the new ICOSahedral Non-hydrostatic (ICON) model, we construct a 60-member ensemble for cases with summertime convection under weak and strong synoptic-scale forcing over central Europe. We find a systematic positive soil moisture–precipitation feedback for all cases, regardless of the type of synoptic forcing, and a stronger response of precipitation to different CCN concentrations and shape parameters for weak forcing than for strong forcing. While the days with weak forcing show a systematic decrease in precipitation with increasing aerosol loading, days with strong forcing also show nonsystematic responses for some values of the shape parameters. The large magnitudes of precipitation deviations compared to a reference simulation ranging between -23% and $+18\%$ demonstrate that the uncertainties investigated here and, in particular, their collective effect are highly relevant for quantitative precipitation forecasting of summertime convection in central Europe. A rainwater budget analysis is used to identify the dominating source and sink terms and their response to the uncertainties applied in this study. Results also show a dominating cold-rain process for all cases and a strong but mostly nonsystematic impact on the release of latent heat, which is considered to be the prime mechanism for the upscale growth of small errors affecting the predictability of convective systems. The combined ensemble spread when accounting for all three uncertainties lies in the same range as the ones from an operational convective-scale ensemble prediction system with 20 members determined in previous studies. This indicates that the combination of different perturbations used in our study may be suitable for ensemble forecasting and that this method should be evaluated against other sources of uncertainty.

1 Introduction

Forecasting convective precipitation remains one of the key challenges in numerical weather prediction (NWP). Many aspects influence the predictability of convective precipitation, e.g., uncertainties in the synoptic-scale flow, inaccuracies in the state of the atmosphere and the underlying land surface, and approximations in the representation of key physical processes in numerical models. Although the processes triggering convection are broadly known, the ability to predict, in particular, severe convective showers is still poor (Jorgensen and Weckwerth, 2003; Bennett et al., 2006; Barthlott and Hoose, 2015). Nowadays, most operational forecasting centers make use of convection-resolving ensemble modeling systems in which uncertainties in the initial and lateral boundary conditions as well as uncertainties in the representation of physical processes are accounted for (e.g., Clark et al., 2016; Barthlott and Barrett, 2020, and references therein). However, these ensemble modeling systems are often underdispersive (e.g., Bouttier et al., 2012; Raynaud and Bouttier, 2017), and the methodology for constructing such ensembles that effectively represent the numerous sources of uncertainty acting in nature remains an active field of research (Keil et al., 2019). To reduce the underdispersion of convective precipitation in convective-scale weather models, other sources of uncertainty need to be assessed. One candidate is the soil moisture content as it controls the partitioning of the available energy at the ground into sensible and latent heat. Land–atmosphere interactions are assumed to be decisive for cloud formation, and subsequent convective precipitation and land-surface properties (e.g., land cover, terrain, and soil texture) are highly heterogeneous across a wide range of spatiotemporal scales. Therefore, it is difficult to establish potential relationships between land-surface variables and atmospheric variables such as temperature and precipitation (e.g., Seneviratne et al., 2010; Schneider et al., 2018; Liu et al., 2022). Many studies have documented the importance of soil moisture for convective precipitation and the complexity of the soil moisture–precipitation feedback, which may vary spatially and temporally (e.g., Pan et al., 1996; Findell and Eltahir, 2003; Hohenegger et al., 2009; Richard et al., 2011; Baur et al., 2018). As was documented by Hauck et al. (2011), soil moisture in models often shows a bias with respect to observations. The initial soil moisture content, however, is of great importance for precipitation forecasting: for drier soils, a systematic positive soil moisture–precipitation feedback was found by Barthlott and Kalthoff (2011), whereas for already relatively wet soils, the influence of increasing soil moisture is much weaker and not systematic anymore. In addition, horizontal land-surface wetness gradients can induce mesoscale circulations leading to convection initiation over dry soils (Taylor et al., 2012; Baur et al., 2018).

Besides the unclear role of the soil moisture–precipitation feedback, there are also large uncertainties arising from the

microphysics of mixed-phase clouds. In current NWP models, aerosol–cloud interactions are considered one of the most uncertain processes (e.g., Tao et al., 2012; Altaratz et al., 2014; Fan et al., 2016; Barthlott and Hoose, 2018). In polluted environments, the activation of aerosol particles (serving as cloud condensation nuclei – CCN) into cloud droplets results in more numerous and smaller cloud droplets. Known as the “lifetime effect”, the onset of precipitation can be suppressed due to a weaker collision–coalescence process, which can result in a longer cloud lifetime (Albrecht, 1989). However, the effects of aerosols on convective precipitation have been shown to vary depending on cloud type, aerosol regime, and environmental conditions (e.g., Seifert and Beheng, 2006b; Khain et al., 2008; van den Heever et al., 2011; Tao et al., 2012; Barthlott et al., 2017). Moreover, there are large uncertainties in the aerosol number concentration because there exist only a few in situ observations or routine measurements of aerosols in three-dimensional space (Thompson et al., 2021).

The cloud droplet size distribution (CDS) is another source of uncertainty in convective precipitation simulations. The form of the underlying generalized Gamma distribution is controlled by the shape parameter ν , which determines the width of the size distribution and also the location of its maximum. Example size distributions illustrating the effect of different shape parameters will be given later in Sect. 2.1. A higher shape parameter suppresses the auto-conversion process of cloud droplets into raindrops, resulting in higher droplet number concentrations (e.g., Seifert and Beheng, 2001). The CDS is also important for the effective radius of cloud droplets, which is the relevant parameter for the radiative properties of clouds. However, the width of the cloud droplet size distribution is not well-constrained by measurements, and a wide range of values (between 0 and 14) based on cloud type and environmental conditions were reported (e.g., Levin, 1958; Gossard, 1994; Miles et al., 2000; Martins and Silva Dias, 2009). There are only a few modeling studies on the effects of the shape parameter available, most based on idealized simulations. For example, Igel and van den Heever (2017) showed with large-eddy simulations of non-precipitating shallow cumulus clouds that changes were on the same order of magnitude as those due to a factor of 16 increase or decrease in aerosol concentration. In a recent work by Barthlott et al. (2022), the relative impact of varying CCN concentrations and different shape parameters of the CDS were assessed for several convective cases over central Europe. They found a large systematic increase in total cloud water content with increasing CCN concentrations and narrower CDSs together with a reduction in the total rainwater content as a result of a less efficient collision–coalescence process. The precipitation response was generally larger for weakly forced cases and averages of Germany, and the timing of convection was not sensitive to different CCN concentrations or shape parameters. Moreover, an increase in the shape parameter can produce almost as large a

variation in precipitation as a CCN increase from maritime to polluted conditions. They also found that increasing CCN concentrations reduced the effective radius of cloud droplets more than larger shape parameters, but cloud optical depth had a similar increase with larger shape parameters to the change in aerosol loading from maritime to polluted. However, the impact of the shape parameter was assessed for one reference CCN concentration only, and the need to determine the impacts of the shape parameter by combined sensitivity analyses was considered to be necessary. Furthermore, the shape parameter is one of the stochastically perturbed parameters in the widely used Thompson–Eidhammer cloud microphysics scheme, and recent model results indicate the suitability of this parameter for generating ensembles at the convective scale (Griffin et al., 2020; Thompson et al., 2021).

While the individual perturbations of parameters or processes have been conducted extensively in recent years, only a few have investigated their combined effects. Imamovic et al. (2017) conducted convection-resolving simulations with a simplified land surface to dissect the isolated and combined impacts of soil moisture and orography on deep-convective precipitation for an initial profile corresponding to typical European summer climate conditions. They found a consistently positive soil moisture–precipitation feedback for horizontally uniform perturbations, irrespective of the presence of low orography. However, a negative feedback emerged with localized perturbations. Other studies with multiple-factor analyses exist mostly for idealized setups, e.g., for investigating the impact of environmental conditions and microphysics on the forecast uncertainty of deep-convective clouds and hail using an emulator approach by Wellmann et al. (2020), for investigating aerosol–cloud–land-surface interaction within tropical sea breeze convection (Grant and van den Heever, 2014) or investigating the relative sensitivity of a tropical deep-convective storm to changes in environmental and cloud microphysical parameters (Posselt et al., 2019). Using the Morris one-at-a-time (MOAT) method for simultaneous perturbations of numerous parameters, Morales et al. (2019) explored the sensitivity of orographic precipitation within the environment of an atmospheric river. Schneider et al. (2019) investigated the relative impact of soil moisture and aerosols combined with orographic effects. They performed simulations with the COSMO (COnsortium for Small-scale MOdeling) model with 500 m grid length for six real-case events over Germany with systematic changes in the initial soil moisture fields and different assumptions about the ambient aerosol concentration. The model produced a positive soil moisture–precipitation feedback for most of the cases, with the soil moisture amount having a stronger effect on precipitation than on its spatial distribution. The precipitation response to changes in the CCN concentration was found to be more complex and case-dependent. However, both aerosols and soil moisture uncertainties were of similar importance for quantitative precipitation forecasting. Baur et al. (2022) stud-

ied the combined impact of soil moisture and microphysical perturbations with the COSMO model for a single case study of locally forced convection in central Europe. They found a large sensitivity of 12 h precipitation deviations ranging between -23% and $+10\%$ compared to a reference run.

In this study, we expand this line of investigation by perturbing the soil moisture, the CCN concentration, and the shape parameter simultaneously using a state-of-the-art operational numerical model. We choose these uncertainties because (i) their individual impact was documented in many recent studies and (ii) all have an impact on the life cycle of convection at different stages from its initiation to the decay. We will investigate the role of different aerosol amounts ranging from low CCN concentrations (representing maritime conditions) to very high CCN concentrations (representing continental polluted conditions), with different values of the shape parameter combined with a wet and dry soil moisture bias. By comparing the effect of ambient aerosol amount to changes in the shape parameter, we can quantify their relative impact on predicting convective precipitation under different soil moisture regimes. We further want to quantify the individual and collective effects of land-surface and microphysical uncertainties on convective-scale predictability for different weather regimes. The combination of different sensitivities will help answer the question of whether and how different processes compensate for or enhance each other and how large the spread of different process pathways is. We can further answer the question of whether and how aerosol effects on clouds are modulated by soil moisture uncertainties (e.g., drier or wetter soils). The unique aspect of this work is that it is the first to systematically evaluate the collective effects of CCN concentrations and uncertainties in the CDS for multiple cases with different synoptic controls and different initial soil moisture contents using a state-of-the-art operational numerical model.

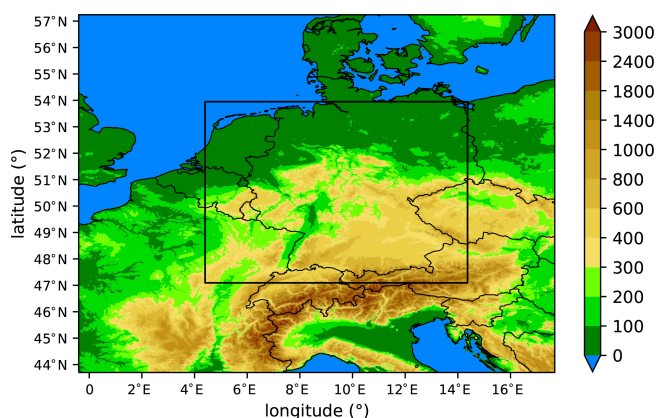
2 Method

2.1 Model description and simulation overview

The model setup is generally similar to that used in Barthlott et al. (2022) but is described here for reference. We use version 2.6.2.2 of the ICOSahedral Non-hydrostatic (ICON) model. ICON is a fully compressible model using an unstructured triangular grid with C-type staggering based on a successive refinement of a spherical icosahedron (Zängl, 2012; Zängl et al., 2015). It can be run in global and limited-area modes with grid-nesting capability. The convection-permitting configuration ICON-D2 at 2 km horizontal grid spacing has been used at the German Weather Service (DWD) for operational forecasts over central Europe since February 2021. Model domain (Fig. 1) and horizontal and vertical resolution used in this study correspond to the operational ICON-D2 configuration. Further model settings are presented in Table 1.

Table 1. Model configuration for the ICON simulations.

Model aspect	Setting
Grid	Unstructured triangular grid R19B07 (2 km grid spacing, 53 8164 cells)
Vertical grid	Vertically stretched smooth level vertical (SLEVE) coordinates (Leuenberger et al., 2010)
Vertical levels	65, 14 levels in the lowest 1000 m, lowest level at 10 m a.g.l.
Model top	23 km
Initial and boundary data	7 km ICON-EU analyses, 3 h update
Time step	20 s
Initialization time	00:00 UTC
Integration time	24 h
Microphysics	Double-moment bulk microphysics (Seifert and Beheng, 2006a)
Heterogeneous ice nucleation	Based on mineral dust concentrations (Hande et al., 2015)
Homogeneous ice nucleation	Following Kärcher and Lohmann (2002) and Kärcher et al. (2006)
Convection parameterization	Deep convection resolved explicitly Tiedtke–Bechtold scheme for shallow convection (Bechtold et al., 2008; Tiedtke, 1989)
Land-surface model	Multi-layer land-surface scheme TERRA (Heise et al., 2006)
Turbulence parameterization	1D based on the prognostic equation for the turbulent kinetic energy (Raschendorfer, 2001)
Radiation scheme	Rapid Radiation Transfer Model (RRTM, Mlawer et al., 1997), called every 12 min
Data assimilation	None

**Figure 1.** ICON simulation domain and model orography in meters above sea level. The black rectangle depicts the evaluation domain covering most of Germany and parts of neighboring countries.

2.1.1 CCN uncertainty

In contrast to the operational setup at the DWD, we use the double-moment microphysics scheme of Seifert and Beheng (2006a) to represent aerosol effects on the microphysics of mixed-phase clouds. This scheme predicts the mass and number concentration of cloud water, rainwater, ice, snow, graupel, and hail and has been extensively used to study

aerosol–cloud interactions in recent years with the ICON model (e.g., Heinze et al., 2017; Costa-Surós et al., 2020; Barthlott et al., 2022) and its predecessor, the COSMO model (e.g., Seifert et al., 2012; Barthlott et al., 2017; Barthlott and Hoose, 2018; Keil et al., 2019; Marinescu et al., 2021). Pre-calculated activation ratios stored in look-up tables (Segal and Khain, 2006) are used to compute the activation of CCN from aerosol particles. The condensation nuclei are all assumed to be soluble and follow a bi-model size distribution (Seifert et al., 2012). Using the Segal and Khain (2006) activation, four different values of the number density of CCN (N_{CCN}) are available, representing maritime ($N_{\text{CCN}} = 100 \text{ cm}^{-3}$), intermediate ($N_{\text{CCN}} = 500 \text{ cm}^{-3}$), continental ($N_{\text{CCN}} = 1700 \text{ cm}^{-3}$), and continental polluted conditions ($N_{\text{CCN}} = 3200 \text{ cm}^{-3}$). Typical conditions of central Europe are represented by the continental aerosol assumption (Hande et al., 2016).

2.1.2 CDSD uncertainty

The second perturbation consists of different widths of the CDSD. The size distribution is based on a so-called generalized Gamma distribution as follows,

$$f(x) = Ax^{\nu} \exp(-\lambda x^{\mu}), \quad (1)$$

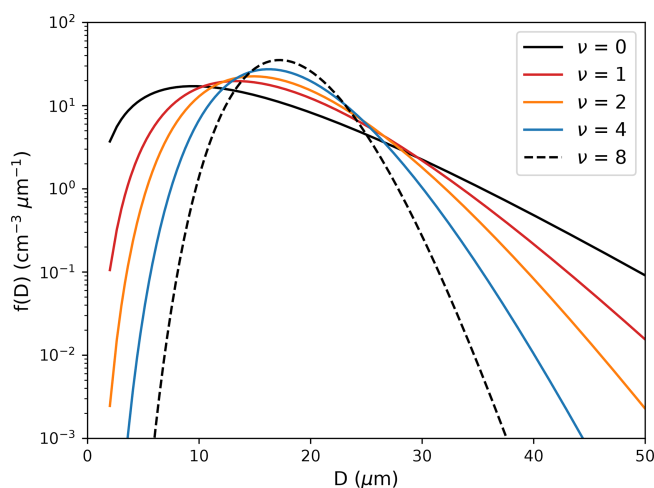


Figure 2. Cloud droplet size distributions for different values of the shape parameter ν at fixed cloud water content ($QC = 1.0 \text{ g m}^{-3}$) and cloud droplet number concentration ($QNC = 300 \text{ cm}^{-3}$). D denotes the diameter of the droplets.

and depends on the shape parameter ν and dispersion parameter μ as a function of the particle mass x . With the predicted mass and number densities, both coefficients A and λ can be calculated (Seifert and Beheng, 2006a). A number of microphysical processes depend directly on the shape parameter (e.g., autoconversion, self-collection) or indirectly (e.g., melting, evaporation, accretion, riming, sedimentation), leading to a potentially large impact of the CDSD on the simulated precipitation totals (Barthlott et al., 2022). In this study, we perturb the shape parameter from 0 to 8. These values lie in the observational range and were shown to have a large impact on convective precipitation forecasts in recent studies (Barthlott et al., 2022; Baur et al., 2022; Matsunobu et al., 2022). The dispersion parameter is kept constant in all simulations ($\mu = 1/3$). To illustrate the impact of the shape parameter on the width of the CDSD, Fig. 2 shows example size distributions as a function of particle diameter D at fixed cloud water content (QC) and cloud droplet number concentration (QNC) for different shape parameters. We refer to Khain et al. (2015) or Barthlott et al. (2022) for the conversion of Eq. (1) from particle mass x to diameter D . It can be seen that larger shape parameters narrow the size distribution and also shift the maximum to larger droplet sizes. An important feature is that, with high shape parameters, the CDSD has fewer smaller droplets but also fewer large droplets, leading to a smaller effective radius, which impacts the optical properties of the clouds.

2.1.3 Soil moisture uncertainty

The third uncertainty included in our combined sensitivity analysis consists of three different soil moisture initializations. Besides a reference run with initial values coming from

the ICON-EU analysis, we conduct simulations with a dry and wet bias ($\pm 25 \%$) to account for uncertainties in soil moisture. The value of 25 % was selected because Hauck et al. (2011) showed that simulated and observed soil moistures in southwestern Germany differ by around 20 %–30 %. Our procedure to include a soil moisture bias is as follows: first, the soil moisture index (SMI) is converted to a volumetric water content (VWC) using the field capacity and the permanent wilting point for each soil type. Then the VWC is increased/decreased by a factor of $\pm 25 \%$ at every grid point at all levels. To ensure physically meaningful values, we restrict the modifications to the limits of the air dryness point and the pore volume for each soil type. Finally, the modified SMI is calculated and written to the file used for model initialization.

In summary, this study investigates the effects of two microphysical uncertainties (i.e., CCN concentration and shape parameter) combined with land-surface uncertainties (soil moisture realizations). By applying four different CCN concentrations, five different shape parameter values, and three soil moisture initializations, we end up with an ensemble of 60 model runs per case. The reference run uses unmodified soil moisture values, a continental CCN assumption typical for central Europe, and a shape parameter of 0. All model runs are abbreviated based on three letters:

1. soil moisture content: dry (DRY), reference (REF), or wet (WET);
2. CCN concentration: maritime (m), intermediate (i), continental (c), or polluted (p);
3. shape parameter ν : 0, 1, 2, 4, or 8.

The reference run would therefore be labeled as run REFc0. Including more microphysical uncertainties (e.g., ice-nucleating particle concentration, hydrometeor sedimentation, or ice multiplication) as in idealized simulations by Wellmann et al. (2020) could be considered in the future but was not done for the moment due to the high number of possible combinations.

2.2 Case studies

We performed numerical simulations for a total of 4 d. To cover different typical weather regimes in central Europe, we selected two cases with weak and strong synoptic forcing, respectively (Table 2). Both weak forcing cases were also used in Barthlott et al. (2022) and the strong forcing case of 17 August 2020 in Matsunobu et al. (2022). The 5 June 2016 case occurred during an exceptional sequence of severe thunderstorms in Germany; its meteorological situation is described in detail by Piper et al. (2016). Mohr et al. (2020) investigated the role of large-scale dynamics in an exceptional sequence of severe thunderstorms of May–June 2018 in Europe to which the 9 June 2018 case belongs. Large amounts of hail

Table 2. List of cases with convective adjustment timescale τ and mean initial relative water content RWC for the three soil moisture scenarios.

Synoptic-scale forcing	Date	τ (h)	RWC (%) (DRY/REF/WET)
Weak	5 June 2016	5.22	55/73/86
Weak	9 June 2018	4.65	28/37/46
Strong	10 June 2019	0.17	24/33/41
Strong	17 August 2020	1.09	25/37/42

fell on 10 June 2019, when a severe storm system was passing over the city of Munich in southeastern Germany. This day was part of a 3 d storm series in June 2019 whose synoptic controls are given in Wilhelm et al. (2021).

To objectively quantify the degree of synoptic-scale forcing, we computed the convective adjustment timescale τ following Keil et al. (2014):

$$\tau = 0.5 \left(\frac{\rho_0 c_p T_0}{L_v g} \right) \frac{\text{CAPE}}{P}, \quad (2)$$

with reference values for density, $\rho_0 = 1.292 \text{ kg m}^{-3}$, and temperature, $T_0 = 273.15 \text{ K}$, specific heat of air at constant pressure c_p , latent heat of vaporization L_v , acceleration due to gravity g , convective available potential energy (CAPE), and the precipitation rate P . It is a measure to distinguish between different flow regimes and can be considered an estimate of the timescale for the removal of conditional instability. Daily mean values of this timescale below a threshold of 3 h indicate strong forcing, higher values weak forcing. A visual inspection of the synoptic weather charts in Fig. 3 confirms the results of the timescale analysis (Table 2).

We now briefly describe the synoptic situation of these cases and the 24 h rain distribution of the respective reference runs. Under weak synoptic forcing, there lies a dominating ridge in central Europe with a ridge axis over the Iberian Peninsula on 5 June 2016 and further to the east on 9 June 2018. On both days, low-pressure systems are situated over the eastern Atlantic. Over Germany, the surface pressure lies between 1012 and 1020 hPa with weak horizontal gradients, and mid-tropospheric winds are weak from the easterly (Fig. 3a) and southwesterly (Fig. 3b) directions. The 24 h accumulated precipitation of the reference runs shows scattered convective showers over Germany for these cases (Fig. 4a, b).

Under strong synoptic forcing, both analyzed days show a stronger baroclinicity of the flow (Fig. 3c, d), with a low-pressure system northwest of France (10 June 2019) and over the eastern Atlantic (17 August 2020). Mid-tropospheric winds are more cyclonic from southwesterly directions, with stronger winds on 10 June 2019 due to deeper low and larger pressure gradients over Germany. The precipitation distribution reveals more organized convection and, especially on 10 June 2019, larger cloud clusters and more long-lived con-

vection. We also compared the simulated precipitation to data from the precipitation analysis algorithm RADOLAN (Radar Online Adjustment) that combines weather radar data with hourly surface precipitation measurements of about 1300 automated rain gauges (not shown). For 24 h accumulated precipitation, we find an overall good agreement, even if the precise locations of individual convective cells are not always simulated at the right place. However, the model succeeds reasonably well in reproducing the observed cloud and precipitation evolution, which implies that these runs serve as a good basis for our combined perturbation experiments.

3 Results

3.1 Precipitation amount and timing

To investigate the response of precipitation amounts to the perturbations applied in this study, we computed domain-integrated precipitation totals for the evaluation domain given in Fig. 1. The percentage deviations for each of the 60 ensemble members from the respective reference run are given in Fig. 5. We see a positive soil moisture–precipitation relationship for the vast majority of the performed simulations, as the accumulated precipitation in most runs with different shape parameters within one CCN concentration increases with increasing soil moisture, independent of the type of synoptic forcing. Although not shown here, the increase (decrease) in the initial soil moisture leads to a systematic increase (decrease) in CAPE and a decrease (increase) in convection inhibition (CIN) for all cases, independent of the microphysical uncertainties. As soil moisture controls the partitioning of the available energy at the ground into latent and sensible heat, the near-surface temperatures show a negative relationship with soil moisture, whereas specific humidity reveals a systematic positive relationship with soil moisture (not shown). This leads to an overall lower level of free convection, resulting in larger amounts of CAPE with smaller CIN despite lower boundary layer heights. However, the soil moisture impact is comparably weaker for the case of 5 June 2016. Especially for polluted conditions, there is only a marginal precipitation increase with soil moisture. This day, however, is characterized by already quite wet initial soils with an average relative water content of 73 % (see Table 2). As was pointed out by Barthlott and Kalthoff (2011), for already quite wet soils, the influence of increasing soil moisture is much weaker and the general response of precipitation to soil moisture is not systematic anymore. For drier soils, however, where evapotranspiration is controlled by soil moisture, a systematic positive relationship of the 24 h accumulated precipitation with soil moisture exists, which can also be found in our simulations. The remaining days have considerably drier initial soil moisture values (36 % on 9 June 2018, 33 % on 10 June 2019, 34 % on 17 August 2020) and reveal a uniform positive soil moisture–precipitation feedback. There is one exception for the case of 9 June 2018:

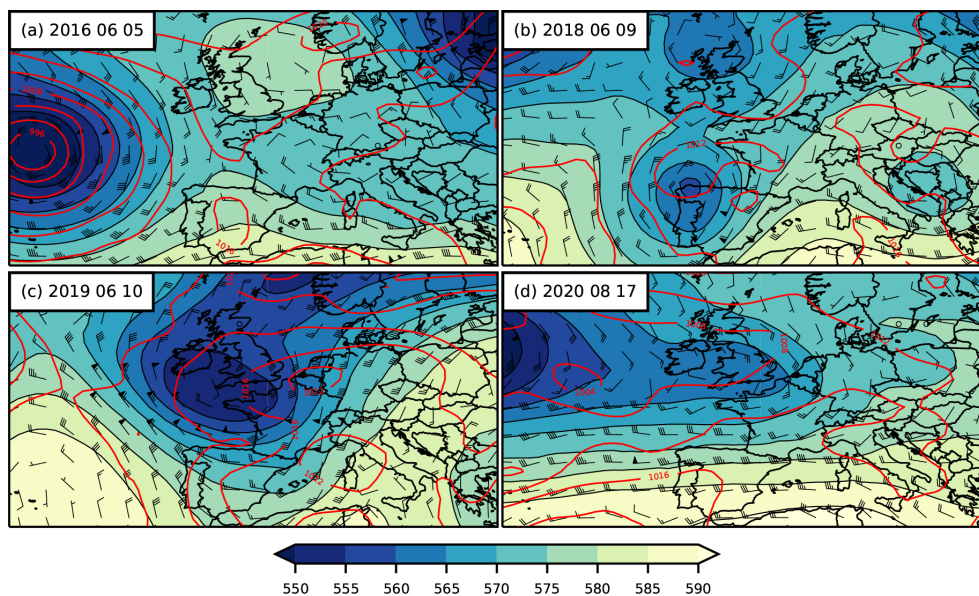


Figure 3. Global Forecast System (GFS) analyses at 12:00 UTC for the cases with weak (**a**, **b**) and strong (**c**, **d**) synoptic-scale forcing showing 500 hPa geopotential height (gpm; shading), sea-level pressure (hPa, red contours), and 500 hPa wind barbs.

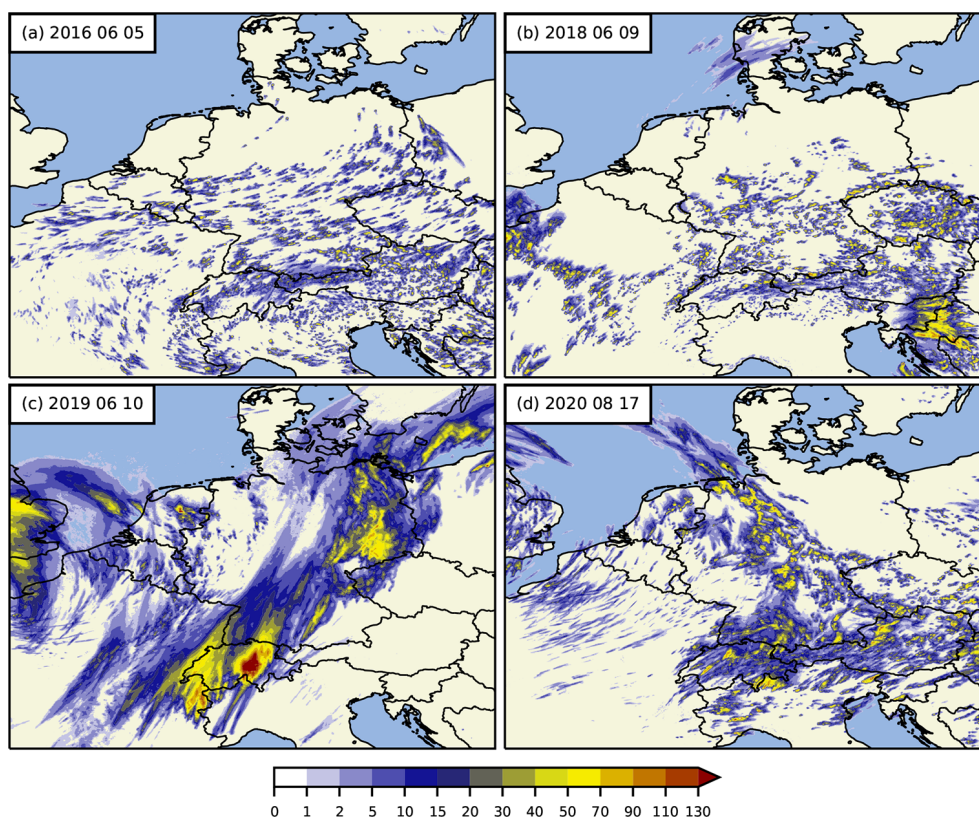


Figure 4. 24 h precipitation amount (mm) of the reference runs with continental CCN concentration, broad cloud droplet size distribution ($\nu = 0$), and reference initial soil moisture for the cases with weak (**a**, **b**) and strong (**c**, **d**) synoptic-scale forcing.

only in the runs with a polluted atmosphere does more rain fall for three of the shape parameter runs in the dry run than in the reference run. On this day, the precipitation amounts in a polluted environment are rather similar in the runs with dry and reference soil moisture. Reasons for that behavior could be related to the fact that a stronger thermal forcing with drier soils compensates for the reduction in CAPE. It is worth noting that, although stronger latent heat fluxes increase near-surface specific humidity, the impact on vertically integrated water vapor is negligible (-1.4% to $+0.8\%$). This is important for the comparability of the runs from our 60-member ensemble. Although this study comprises only three different soil moisture realizations, we tested whether there is a linear response of accumulated precipitation to the initial soil moisture. Recently, a modeling study by Drager et al. (2022) has suggested a new type of rainfall response to soil moisture in which intermediate-moisture soils receive less rainfall than do the driest or wettest soils. This non-monotonic soil moisture–precipitation relationship was found to result from the permanent wilting point’s modulation of transpiration of water vapor by plants. Our simulations revealed a monotonic soil moisture–precipitation relationship for all runs under strong synoptic forcing and for 85 % of the runs under weak synoptic forcing. Mean correlation coefficients were also high and ranged between 0.914 and 0.988. For more robust results, however, a higher number of soil moisture scenarios as applied in Drager et al. (2022) or Barthlott and Kalthoff (2011) would be necessary.

The response of total precipitation to varying CCN concentrations shows a systematic precipitation decrease with increasing CCN concentrations for the weak forcing cases, irrespective of the underlying soil moisture content. This general trend is also apparent for the strong forcing cases; however, there are some shape parameter runs that deviate from this systematic behavior: e.g., for the runs at the reference soil moisture, the intermediate CCN concentrations with shape parameters between 2 and 8 reveal larger rain amounts than with maritime CCN concentration for the 10 June 2019 case. The same applies to the case of 17 August 2020 in wet soils from continental to polluted conditions with a shape parameter of 0. However, the magnitude of the CCN response for the strong forcing cases is much lower (-16.4% to $+11.5\%$) than for weak forcing (-23% to $+18\%$), which is in agreement with previous findings regarding aerosol–cloud interactions with the COSMO model (Barthlott and Hoose, 2018; Keil et al., 2019) and with ICON (Barthlott et al., 2022). Note that different models may produce different responses to aerosol perturbations, but these studies used the same double-moment scheme for simulating convective episodes over central Europe. The validity of the convection invigoration mechanism proposed in Rosenfeld et al. (2008) is still open, and many studies documented a decrease in total precipitation with increasing aerosol concentrations (e.g., Tao et al., 2012; Storer and van den Heever, 2013). Using idealized simulations, Grant and van den Heever (2015) showed

that the influence of aerosols varies inversely with storm organization, and Fan et al. (2009) found that vertical wind shear qualitatively determines whether aerosols suppress or enhance convective strength.

It is further of interest to analyze the impact of different shape parameters on precipitation deviations. For the weak forcing cases, there is only a small sensitivity of total precipitation for maritime and intermediate CCN concentrations. For more polluted environments (runs c and p), the sensitivity to the shape parameter becomes much larger, and precipitation amounts tend to decrease with larger values of the shape parameter. The shape parameter impact for the strong forcing cases remains generally small in all the soil moisture and CCN concentration regimes. Furthermore, there is no observable systematic effect on precipitation totals. Only for runs DRYc0 to DRYc8 on 10 June 2019 is there a systematic precipitation increase with somewhat stronger precipitation deviations compared to the other cases.

A feature only apparent for weak synoptic forcing is the fact that for maritime and intermediate CCN concentrations in dry soils, more precipitation is simulated, as with reference soil moisture and continental conditions. The enhanced warm-rain process together with the stronger thermal forcing seems to balance the CAPE reduction for drier soils. For the strong forcing case of 17 August 2020, the maritime and intermediate runs with drier soils simulate similar precipitation amounts to the reference run. Obviously, the enhanced warm-rain process roughly balances the reduction in CAPE. To support this statement, we calculated the percentage deviations of CAPE and autoconversion/accretion of those model runs to the reference run. We find that the percentage magnitudes are almost identical: CAPE decreases by 11.8 %, whereas the warm-rain process increases by 11.5 %. Although these variables cannot be used to quantitatively determine their impact on the total rain amount, this nevertheless supports our hypothesis that the CAPE reduction with drier soils can be compensated by the effects of a strengthened warm-rain process. Interestingly, the reference runs in both cases with weak forcing still have larger precipitation amounts than those from the wet scenario with polluted CCN concentrations. This points towards a dominating precipitation reduction by a reduced collision–coalescence process over a soil moisture increase due to higher instability. An important result is that an increase in the shape parameter can cause almost as large a change in precipitation totals as a CCN increase from maritime to polluted conditions, and for weak forcing cases, the shape parameter has a larger effect on precipitation totals in polluted environments.

For a more complete picture of the rain response to our microphysical and land-surface perturbations, we also analyze the fraction of cloudy grid points of each model run. We find a mostly systematic increase in cloud cover with increasing CCN concentrations and larger shape parameters (not shown). Although the relative changes are considerable (-13% to $+29\%$), the absolute changes are much smaller

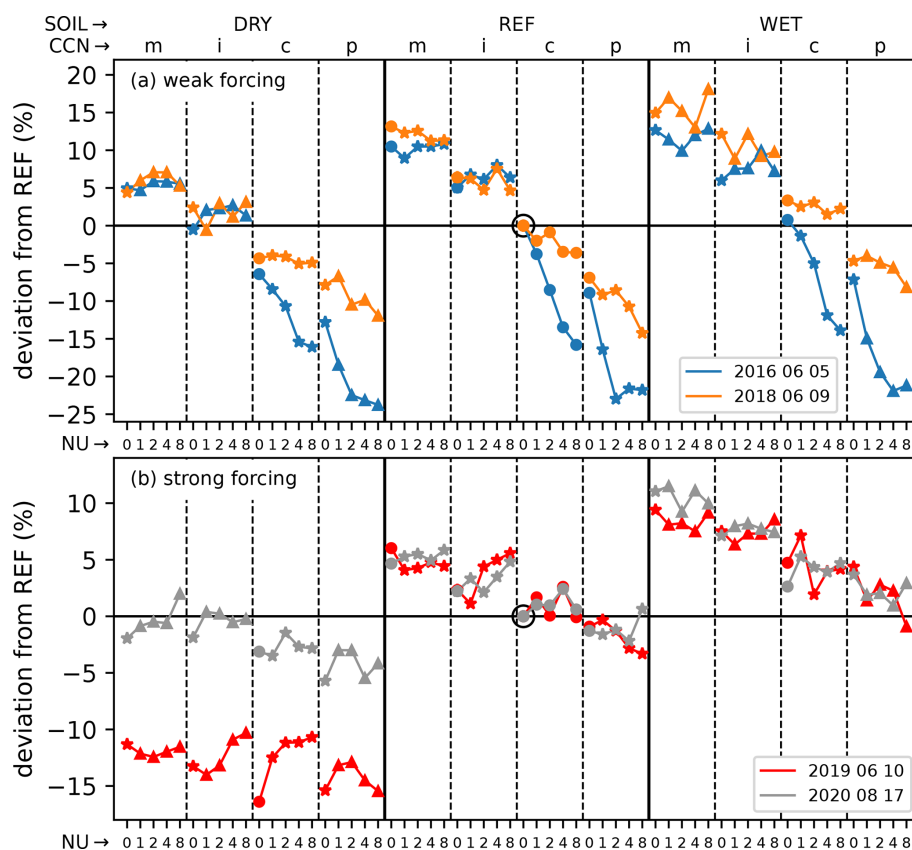


Figure 5. Precipitation deviation from the respective reference run (marked with a black circle) for (a) weak and (b) strong synoptic forcing. Data points are arranged in three blocks with different soil moisture contents (DRY, REF, WET), each of which is divided into four blocks with increasing CCN concentration (m, i, c, p). The points inside one CCN concentration then indicate the sensitivity with respect to the shape parameter (NU) from 0 to 8. The type of marking distinguishes between single effects (circles), double synergies (stars), and triple synergies (triangles).

and range between +1 % and +3 %. Nevertheless, the increase in cloud cover seems contrary to the mostly decreasing total precipitation amounts with increasing CCN concentration and increasing shape parameter (see Fig. 5). The answer to this is twofold: (i) the reduced warm-rain process as a result of a less efficient collision–coalescence process leads to a longer cloud lifetime, or (ii) stronger rain intensities must compensate for the smaller cloud cover. We therefore now analyze the daily cycle of 30 min precipitation rates to investigate the reasons for the strong effects on precipitation totals and to assess whether longer/shorter lifetimes or increased/reduced rain rates are simulated by the model.

The first case of 5 June 2016 is characterized by a similar diurnal cycle in all runs, indicating that the initiation of convection is, on average, not sensitive to the perturbations applied in this study (Fig. 6). However, the maximum precipitation intensities are strongly modified, ranging from 0.15 mm (30 min^{−1}) to 0.25 mm (30 min^{−1}). The higher the CCN concentration, the lower the rain intensities. The range of the shape parameter runs within one CCN concentration increases with higher CCN concentrations. These features

explain the lower precipitation amounts and the stronger precipitation deviation in polluted environments found in Fig. 5. The second weak forcing case (9 June 2018) generally shows a similar behavior. On this day, we also see a soil moisture impact: in the wet scenario, the increase in precipitation rates after 09:00 UTC is weaker than in the reference run. As the resulting maximum precipitation rates later on are mostly larger than with the reference soil moisture and precipitation rates at the end of the simulation time (21:00–00:00 UTC) are still higher than in the REF run (probably due to the larger amounts of CAPE), precipitation totals are larger than in the REF run.

The two strong forcing cases are characterized by larger mean rain intensities than the weak forcing cases as the ratio of rainy grid points is higher (see the precipitation distribution in Fig. 4). As the timing is again broadly similar and the spread in rain intensities is generally smaller, the total sensitivity to our perturbations is less than for weak forcing, in agreement with the findings for the total precipitation deviations (Fig. 5). For both strong forcing cases, a systematic soil moisture impact is present: the higher the soil moisture,

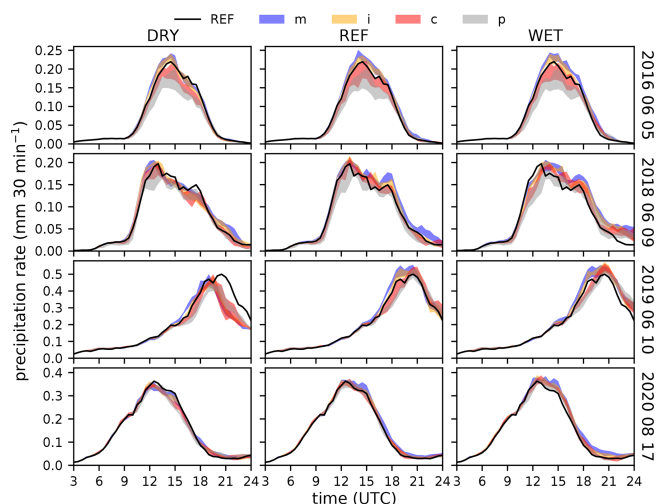


Figure 6. Domain-averaged precipitation rates for weak forcing (rows 1 and 2) and strong forcing (rows 3 and 4) for dry (left), reference (middle), and wet soil conditions (right). The color-coded areas indicate the range between the minimum and maximum precipitation rate for all shape parameter sensitivities within one CCN concentration. Different colors indicate the four different CCN concentrations. The black lines indicate the respective reference runs with reference soil moisture, continental CCN concentration, and a shape parameter of 0.

the higher the maximum rain intensities, which is most likely a direct effect of the CAPE increase. In addition, maximum precipitation rates in the dry runs for 10 June 2019 occur 1–2 h earlier than in the reference run. The earlier decaying phase of convection is then responsible for the strong total precipitation reduction on that day. The case of 17 August 2020 shows increasing precipitation rates with higher soil moisture, although the increase is less pronounced than on 10 June 2019. Again, the largest precipitation rates are found for maritime CCN concentrations, and the spread with respect to different shape parameters remains small.

In order to quantify the ensemble spread, we computed the domain average of the grid-point-based normalized standard deviation S_n as follows (see, e.g., Keil et al., 2019):

$$S_n(x, y) = \frac{1}{P(x, y)} \sqrt{\frac{1}{N-1} \sum_{i=1}^N \{P(x, y) - P_i(x, y)\}^2}. \quad (3)$$

$P_i(x, y)$ denotes the hourly precipitation of member i , $P(x, y)$ represents the ensemble mean hourly precipitation, and N is the ensemble size. The normalization of the spread is done in order to remove fluctuations that are due to the diurnal variation of precipitation. Besides an ensemble spread based on all 60 members, we also computed the spread induced by soil moisture, CCN, and the shape parameter individually. As only three soil moisture regimes are available for each identical CCN concentration and shape parameter, we used the bootstrapping method to randomly pick between

different suitable combinations to calculate their normalized spread. This procedure was repeated 100 times. The results show that the area-averaged local precipitation variability introduced by varied CCN concentrations and shape parameters is rather similar (Fig. 7). This finding holds true for all days irrespective of the synoptic-scale forcing. For both uncertainties, the variability increases rapidly already in the first hours of the forecast, followed by a rather constant plateau until a further increase occurs in the afternoon at the peak of convective activity (see the rain rates in Fig. 6). In contrast to that, the variability due to soil moisture reveals a weaker increase early in the simulation and reaches similarly high values (or even higher ones on 9 June 2018) to CCN and shape parameter variability only around noon. In the afternoon, a similarly weak increase is simulated, as in the other types of uncertainty. Later, soil moisture variability remains slightly below the ones from the CCN and shape parameter. For a high-impact weather period of 2016, Keil et al. (2019) found that the spread induced by soil moisture was slightly larger than the one induced by different CCN concentrations in the afternoon. However, in their study soil moisture was perturbed by applying high-, low-, and band-pass filters to introduce surface perturbations, which is different from our approach of using a soil moisture bias. Figure 7 further reveals that the overall ensemble spread when accounting for all three uncertainties during the active convective period lies between 2.2 and 4.1. More importantly, the absolute values lie in the same range as the ones from the operational convective-scale COSMO ensemble prediction system with 20 members at that time (Keil et al., 2019). This indicates that the combination of different perturbations used in our study may be suitable for increasing the variability and reducing the underdispersion of convective precipitation and that this method should be evaluated against other sources of uncertainty.

The spread of the model results and the impact of double and triple synergies have been demonstrated so far with precipitation deviations, precipitation intensities, and the normalized ensemble spread. Although the quantitative interpretation of nonlinear interactions is not the main focus of this study, we used the factor separation methodology of Stein and Alpert (1993) in order to understand how aerosols, the shape parameter, and soil moisture may interact synergistically. This methodology is a simple way of showing how multiple factors and their nonlinear interactions influence a predicted field and has been applied many times in the atmospheric sciences, e.g., for aerosol–cloud–land-surface interactions within tropical sea breeze convection (Grant and van den Heever, 2014) or for the effects of topography, convection, and latent and sensible heat fluxes on Alpine lee cyclogenesis (Alpert, 2011). For the four cases analyzed here, we find that the single impact of changing one parameter has a much weaker response than the double or triple synergies (not shown). Furthermore, all double synergies work to enhance accumulated precipitation, whereas all triple synergies-

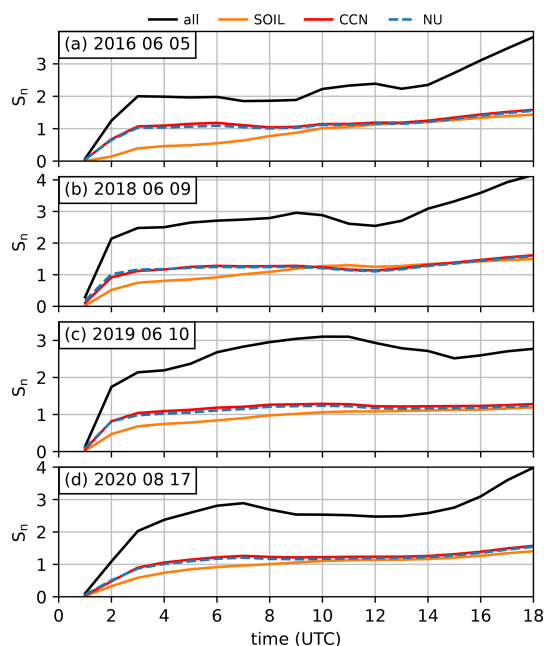


Figure 7. Domain-averaged normalized ensemble spread S_n based on hourly precipitation amounts evaluated for different uncertainties (soil moisture SOIL, cloud condensation nuclei CCN, and shape parameter NU).

tic interactions reduce the precipitation, in agreement with findings from Grant and van den Heever (2014). The triple synergies are greater than the double synergies by a factor of approximately 3. Whereas the factor separation for the single impacts is always correlated with the rainfall difference compared to the respective reference run, the double and triple synergy terms rather represent the contributions of the synergistic interactions that occur. We must emphasize that synergy terms may not be meaningful for a field that has a finite range like total precipitation and when individual impacts of one parameter dominate the change in precipitation. Nevertheless, the results from the factor separation and ensemble spread shown before demonstrate the importance of considering synergistic effects for convective-scale predictability.

3.2 Hydrometeor contents and microphysical process rates

To understand the impact of our perturbations on the precipitation amount and timing, we now analyze vertically integrated hydrometeor contents (Fig. 8). We find a systematic increase in total cloud water with increasing CCN concentration and also with increasing shape parameters. This can be attributed to a reduced warm-rain process, which is in agreement with previous studies (e.g., Tao et al., 2012; Storer and van den Heever, 2013; Barthlott and Hoose, 2018; Barthlott et al., 2022). We find a strong systematic reduction in auto-conversion and accretion rates with larger aerosols and larger

shape parameters (not shown). Especially for maritime CCN concentrations, the impact on the autoconversion process is substantial and ranges from a more than 800 % increase with a low shape parameter to a 11 % increase for a shape parameter of 8 compared to the respective reference run. Interestingly, total cloud water contents are almost independent of the initial soil moisture. The spread of the runs with different shape parameters is larger for polluted environments. The impact of the microphysical uncertainties is substantial, with reductions of more than 50 % and increases of more than 150 %.

For total rainwater, we find an opposite behavior to that of cloud water, namely, a systematic negative response to higher CCN concentrations and shape parameters. In contrast to cloud water, the spread of shape parameter runs is rather similar in all CCN regimes. The overall response is smaller than for cloud water but still large and ranges between −55 % and +58 % compared to the reference run. There is also a very weak sensitivity to soil moisture but with positive and negative relationships depending on the day and specific configuration. An important finding is the fact that the percentage range is rather similar for different CCN concentrations and different shape parameters, indicating that the CCN concentration and the shape parameter are equally important for total rainwater deviations. For both cloud water and rainwater, the weak forcing cases show a stronger sensitivity than the ones with strong synoptic forcing.

The total ice content increases with higher CCN concentrations but shows a remarkable feature: for rather clean environments (i.e., maritime and intermediate runs), the total ice content is not sensitive to different shape parameters and remains constant in all runs with the respective CCN concentrations. Only the intermediate CCN concentration with large shape parameters of $\nu = 8$ shows a weak increase in total ice. With larger aerosol amounts, there is also a strong dependence of the ice content on the shape parameter. The strongest increase is simulated for polluted environments, with an increase of +66 % to +309 % on 5 June 2016 compared to the reference run. The positive relationship with the aerosol content was also found by Barthlott et al. (2022) and is probably related to the larger water load at higher levels caused by the reduced warm-rain process. The independence of the ice content from varied shape parameters in cleaner environments can be explained by the response of heterogeneous and homogeneous freezing rates to our perturbations. We find that, in all cases, there is almost no dependence of homogeneous freezing with varied shape parameters, whereas under continental and polluted conditions, a strong sensitivity exists (not shown). Heterogeneous freezing, although mostly much smaller than homogeneous freezing, only reveals a small sensitivity to different shape parameters in clean environments. We therefore conclude that smaller amounts of supercooled liquid water with a broad size distribution in cleaner environments are less susceptible

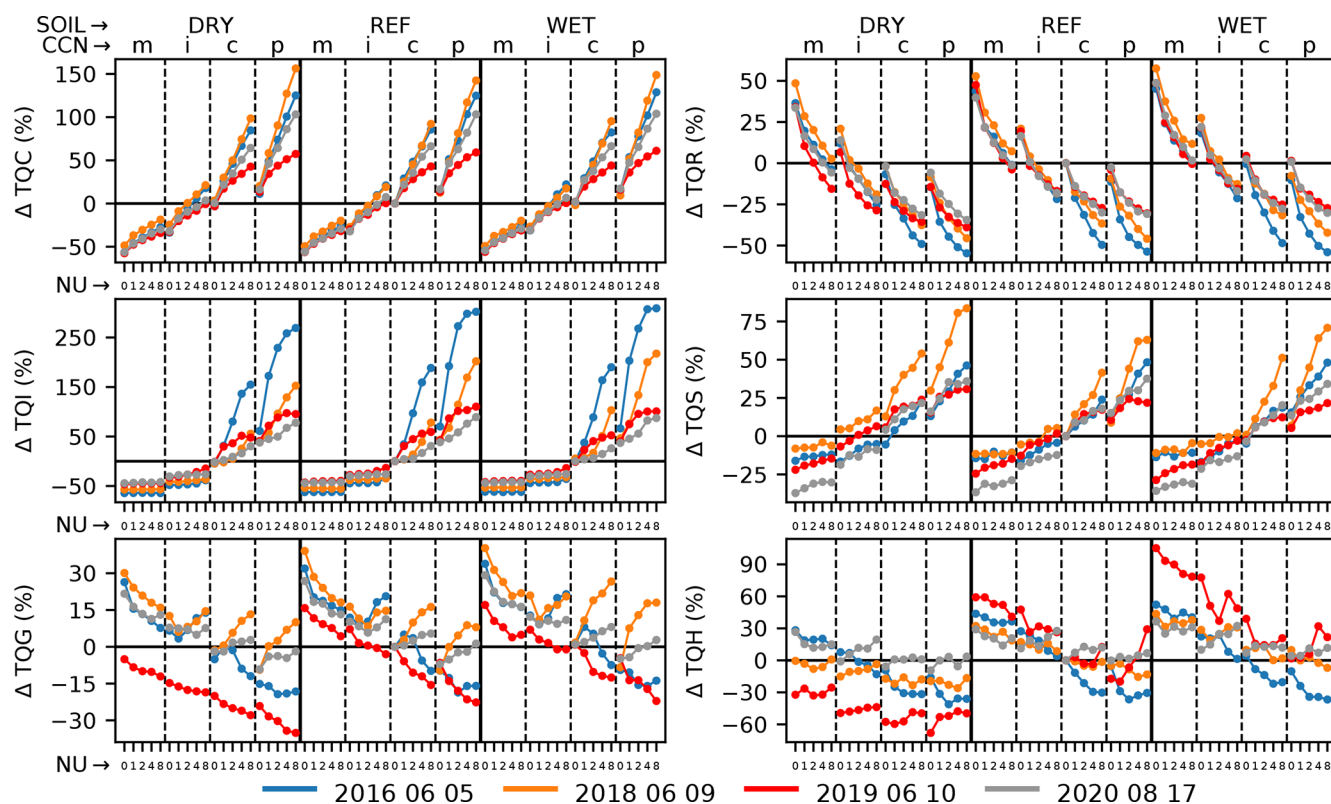


Figure 8. Percentage deviations from the respective reference runs of spatiotemporal averages of total cloud water (TQC), rainwater (TQR), ice (TQI), snow (TQS), graupel (TQG), and hail (TQH). Data points are arranged as in Fig. 5.

to the impact of narrowing the size distribution with varied shape parameters.

The total snow content generally increases with larger aerosol loads and also shows a weak increase to larger shape parameters at maritime and intermediate CCN concentrations. The spread of the different shape parameter runs increases with CCN concentrations. The overall response is smaller than the one from ice, i.e., -37% to $+84\%$. Both the ice and the snow content are rather independent of the initial soil moisture assumption.

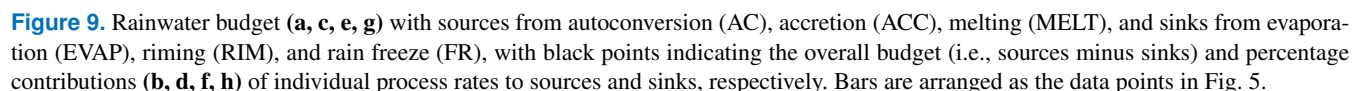
A more complex response is simulated for the total graupel content. For 10 June 2019, the model simulates an increase with soil moisture, an increase with CCN concentration, but a mostly systematic decrease with increasing shape parameters. The remaining three cases show a weak response to soil moisture only and, especially at higher CCN concentrations, also an increase with larger shape parameters. Similar results were found by Barthlott et al. (2022), where some of the days show a graupel increase and others a decrease with narrower CDSD. Comparing the absolute graupel contents of the cases analyzed reveals that the case of 10 June 2019 has a much larger graupel content than the remaining three cases. Some of the cases show a decrease in graupel mass for maritime CCN conditions and an increase for higher CCN concentrations. This can be attributed to graupel/hail riming

with cloud droplets, which increases with larger shape parameters for already narrower size distributions (not shown). Overall, the total graupel content exhibits a smaller response than snow (-35% to $+40\%$). The total hail content shows a strong response to soil moisture for the case of 10 June 2019 and a weaker but still positive response for the remaining three cases. The CCN impact is mostly negative: only some runs with larger shape parameters reveal an increase in polluted environments. The impact of larger shape parameters is weaker than the one from CCN and is mostly negative or neutral.

It is now of interest to study the contribution of individual microphysical processes to the production and loss of rainwater and to analyze the sensitivity to and the magnitude of the perturbations applied in this paper. We therefore computed a rainwater budget (B) that consists of the sources autoconversion (AC), accretion (ACC), and melting (MELT) and sinks from evaporation (EVAP), riming (RIM), and rain freeze (FR) as follows:

$$B = AC + ACC + MELT - EVAP - RIM - FR. \quad (4)$$

We apply Eq. (4) to domain averages of vertically integrated and time-accumulated process rates (Fig. 9). It can be seen that the melting of frozen hydrometeors dominates the contribution to rainwater production and always has a contribu-



The dominant sink term in our budget analysis is rain evaporation, followed by riming. The freezing of rain is below 5 % for both strong forcing cases and on 9 June 2018, but on 5 June 2016, the contribution is larger (4 %–11 %). The response of the relative contributions from evaporation and riming to CCN and shape parameters is rather weak and non-systematic. The absolute values of riming decrease in a systematic way with increasing CCN concentrations but show no systematic reaction to variations in the shape parameter. The response of raindrop evaporation reveals a feature already found in earlier work (e.g., Barthlott et al., 2022): total evaporation rates are highest for clean environments and systematically decay with both increasing CCN and larger shape parameters. The combined effect of high aerosol loads with narrower size distributions by larger shape parameters can lead to an evaporation increase of 57 % and a 30 % reduction compared to the reference simulation. This large ef-

fect can be related to the raindrop size distribution. As the aerosol concentration and shape parameter are increased, the size distribution shifts to populations of raindrops that are fewer in number but larger in size, and evaporation is reduced due to the smaller surface area of large raindrops relative to their volume (see, e.g., Storer et al., 2010; Barthlott et al., 2017). The sum of all source terms decreases with increasing CCN concentrations and larger shape parameters. However, as the sink terms also reveal a reduction in magnitude, the net rainwater budget is reduced less than expected from the reduced source terms. We also see a weak positive soil moisture impact which was already apparent in the analysis of the surface rain amounts (Fig. 5).

It is also of interest to assess the relative role of warm-rain and cold-rain processes and how they depend on the microphysical and land-surface uncertainties applied in this study. Therefore, we inspect the ratio of cold-rain formation (vapor deposition and riming) to warm-rain formation (autoconversion and accretion) integrated over the entire simulation time (Fig. 10). Our simulations show that, on average, the cold-rain contribution dominates the rain formation for all days. In agreement with the reduction in autoconversion and accretion documented earlier, the relative role of the processes via the ice phase increases with larger shape parameters and increased CCN concentrations. It is also evident that the higher the CCN concentration, the larger the response to varied shape parameters. For example, on 6 June 2018, the shape-parameter-induced increase in the maritime environment is from a ratio of 1.38 to 1.94 (increase factor 1.41), whereas in the polluted environment, the increase is from 1.26 to 4.48 (increase factor 3.6) in the runs with drier soil moisture. The higher shape parameter sensitivity in polluted conditions was also seen, e.g., for total hydrometeor contents (see Fig. 8). As expected, the case with the highest ice water path (10 June 2019) shows the largest ratio of cold-rain to warm-rain formation of all analyzed cases. The ratios found with our ICON simulations lie in a similar range to previous COSMO simulations using the same two-moment microphysics scheme (Barthlott and Hoose, 2018; Baur et al., 2022).

3.3 Impact on latent heat release and updraft velocities

Microphysical processes have an impact on atmospheric dynamics, in particular via the release of latent heat during condensation, deposition, riming, or freezing. Latent heat release in regions of precipitation is considered to be the prime mechanism for the upscale growth of small errors affecting the predictability of convective systems (e.g., Selz and Craig, 2015). Whereas the relative role of cold-rain processes increases with narrower size distributions (see Fig. 10), the absolute values are declining (see the budget analysis in Sect. 3.2). This is the reason why the release of latent heat shows an opposing response to the ratio of cold-rain to warm-rain formation (Fig. 11a). For maritime CCN concentrations,

the model simulates a mostly systematic decreasing latent heat release. There is not much of a sensitivity of the latent heat release to different shape parameters in the intermediate CCN regime, and for larger aerosol loads (continental, polluted), the shape parameter sensitivity is case-dependent, where either an increase or a decrease is simulated. Compared to the respective reference run, the magnitude of the latent heat response is quite large and ranges between -19.4% and $+24.5\%$. There is also a weak positive soil moisture response for most cases, with again the strong forcing case of 10 June 2019 showing the strongest impact.

To study the impact on the dynamics, we computed spatiotemporal averages of updraft velocities (i.e., only positive values were accounted for) for cloudy grid points defined with a total cloud water content larger than 0.3 kg m^{-2} (Fig. 11b). For this analysis we selected the vertical updrafts at a height of 5 km a.g.l. because mean profiles reveal a systematic response of updraft velocities throughout the entire troposphere and the maximum differences between different aerosol loads occur between 5 and 6 km a.g.l. The largest updraft velocities occur for maritime CCN concentrations and low shape parameters. The mean updraft speeds then decline with larger aerosol loads. For almost all analyzed cases, the updraft strength also declines with larger shape parameters. The impact is larger in clean environments, irrespective of the initial soil moisture assumption. Compared to the reference simulation, the differences are substantial ($+78\%$ to -31%). The decline of updraft strength mostly follows the decline of latent heating, but at continental and polluted CCN concentrations, there are some cases that are not correlated well. However, the overall correlation of all data points within one soil moisture regime is still very high and ranges between 0.81 and 0.9 (not shown). As in previous studies with the ICON model (Barthlott et al., 2022), there is no CCN-induced convective invigoration as the updraft strength always declines with increasing CCN concentrations. In contrast to the theory suggested by Rosenfeld et al. (2008), the higher number concentrations of cloud droplets and the larger water load in the mixed-phase region do not increase latent heating in our simulations. Thus, updrafts are less buoyant and convection is not invigorated. However, the validity of the invigoration hypothesis remains open as there are contradictory results depending on the details of the microphysics scheme, the environmental conditions, or the cloud type (e.g., Altaratz et al., 2014; van den Heever et al., 2011; Fan et al., 2017). A recent study of Igel and van den Heever (2021) used theoretical calculations to demonstrate that a CCN-induced increase in storm updraft velocity is theoretically possible but much smaller (and often negative) than earlier calculations suggested.

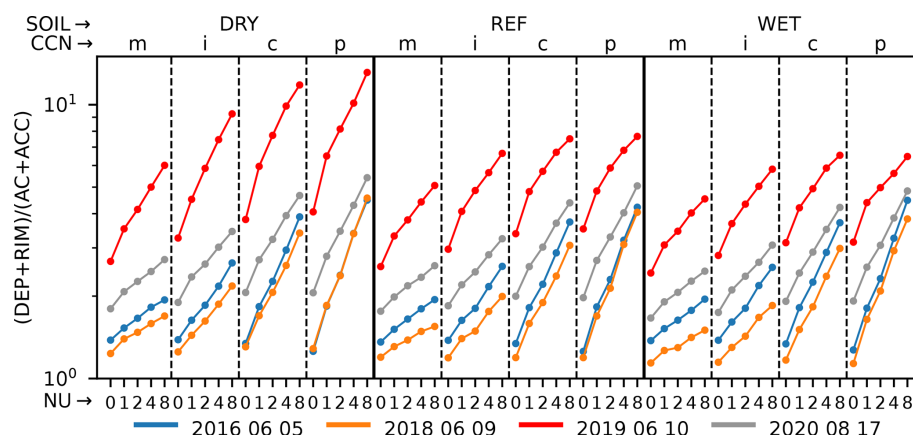


Figure 10. Ratio of cold-rain formation (deposition DEP and riming RIM) to warm-rain formation (autoconversion AC and accretion ACC). Data points are arranged as in Fig. 5.

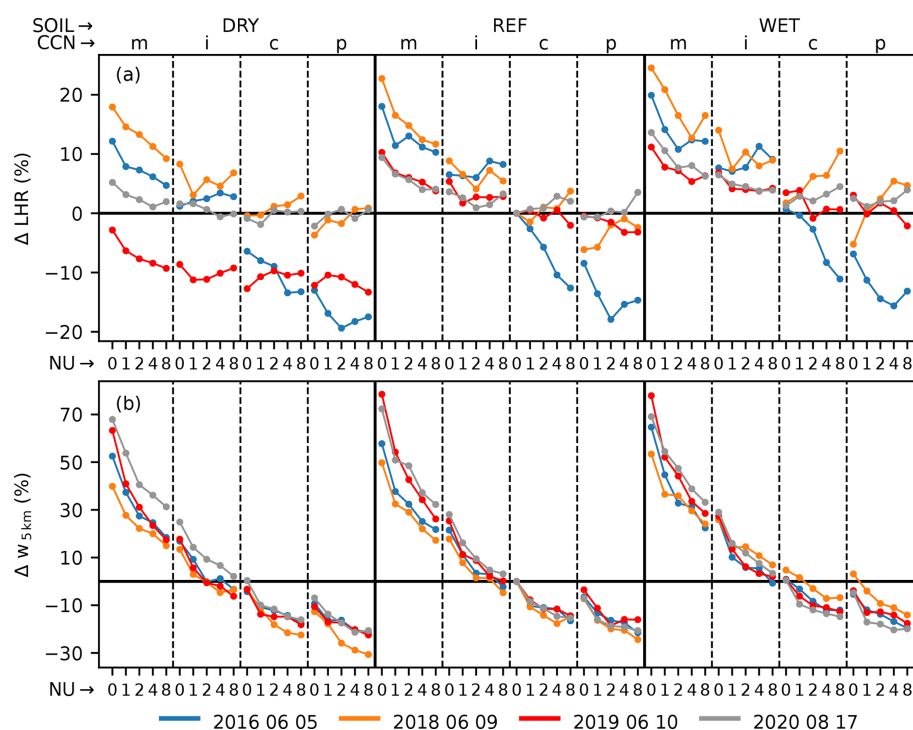


Figure 11. Percentage deviations of latent heat release (LHR) (a) and deviations of updraft velocities w at 5 km a.m.s.l (b). The latter were calculated for cloudy grid points only, for which vertically integrated total cloud water content is larger than 0.3 kg m^{-2} . Data points are arranged as in Fig. 5.

4 Summary and conclusions

The purpose of this study was to quantify the individual and collective effects of land-surface and microphysical uncertainties and to assess their impacts on convective-scale predictability. We therefore constructed a 60-member ensemble with the ICON model for four cases with different synoptic-scale forcing. The ensemble consists of combined perturbations of varied aerosol concentrations (maritime to polluted), different shape parameters of the cloud droplet size distribu-

tion (0–8), and different initial soil moisture conditions (dry and wet bias). We find a systematic positive soil moisture–precipitation feedback for all cases, independent of the type of synoptic forcing as a result of higher instability. The precipitation response to different CCN concentrations and the shape parameter is stronger for weak forcing than for strong forcing, in agreement with previous studies (e.g., Schneider et al., 2019; Keil et al., 2019; Barthlott et al., 2022). While the days with weak forcing show a systematic decrease in

precipitation as the aerosol load increases, days with strong forcing also show nonsystematic responses for some shape parameter values. For weak forcing, the response to the shape parameter is small for maritime and intermediate CCN concentrations but becomes much larger in polluted environments. On the other hand, the shape parameter impact remains generally small in all soil moisture and CCN concentration regimes for the strong forcing cases, and no systematic effect on precipitations totals can be identified. Based on the magnitude of the total precipitation response ranging between -16.4% and $+11.5\%$ for strong forcing and between -23% and $+18\%$ for weak forcing, we conclude that the uncertainties investigated here and, in particular, their collective effects are highly relevant for quantitative precipitation forecasting of summertime convection in central Europe. These values gain even more importance if we consider that they are mean values over a large area and that the location and intensity of precipitation certainly vary locally, with further implications for hazard assessments of convective storms. In some cases, we also find compensating effects of different disturbances. For example, the enhanced warm-rain process in clean environments can offset the CAPE reduction for drier soils and lead to an increase in precipitation compared to the reference run.

The analysis of the cloud fraction and rain intensities revealed that the overall timing of convection is not sensitive to the microphysical perturbations applied in this study. From this it can be concluded that different rain amounts are only caused by stronger or weaker rainfall intensities. The maximum rain intensities are higher for clean environments with a broad drop size distribution. An important finding is the fact that the combined ensemble spread when accounting for all three uncertainties lies in the same range as the ones from the operational convective-scale COSMO ensemble prediction system with 20 members determined in previous studies (Keil et al., 2019). Similarly, the factor separation methodology showed a larger impact of triple synergies on the simulation results compared to double synergies or single impacts, which demonstrates the importance of considering synergistic effects for convective-scale predictability. To our knowledge, only Grant and van den Heever (2014), Park and van den Heever (2022), and Baur et al. (2022) have studied synergistic effects of aerosols and soil moisture so far. Grant and van den Heever (2014) conducted idealized cloud-resolving simulations of tropical sea breeze convection and found precipitation reductions by over 40 % and 50 % for the most extreme perturbations. Park and van den Heever (2022) performed two large idealized 130-member ensembles that represent different initial conditions typical of tropical sea breeze environments in which they simultaneously perturbed six atmospheric and four surface parameters. Comparisons of the clean and polluted ensembles demonstrated that aerosol direct effects reduce the incoming shortwave radiation as well as the outgoing longwave radiation within the polluted ensemble and that enhanced aerosol loading re-

sults in a weakening of the convection initiated along the sea breeze front. The realistic convection-resolving simulations of Baur et al. (2022) were conducted for a single case study only, but they found a similar sensitivity of precipitation deviations to this study (-23% and $+10\%$).

The analysis of vertically integrated hydrometeor contents shows a strong systematic increase in total cloud water content with increasing CCN concentrations and larger shape parameters along with a decrease in total rainwater content. This could be attributed to a systematic decrease in the warm-rain processes of autoconversion and accretion. The impact of the microphysical uncertainties is substantial, with variations in total cloud water ranging between -50% and $+150\%$ and in rainwater between -55% and $+58\%$ compared to the reference run. Interestingly, cloud ice is insensitive to shape parameter variations in clean environments, whereas the CCN-induced ice increase is fostered with larger shape parameters in polluted environments. It is hypothesized that the smaller amounts of supercooled liquid water with a broad size distribution in cleaner environments are less susceptible to the impact of narrowing the size distribution with the shape parameter. The results from a rainwater budget analysis revealed that melting of frozen hydrometeors is dominating the rain production, followed by accretion and an only minor contribution from autoconversion. Whereas the contribution of melting increases with larger shape parameters, the one from accretion decreases. This opposing response highlights the greater importance of the cold-rain processes when the warm-rain process is reduced. The evaporation of raindrops proved to be by far the most important sink term, with the largest values occurring in clean environments with broad size distributions. Larger aerosol loads and/or higher shape parameters lead to raindrop distributions that are larger in size and therefore less susceptible to evaporation. The sum of all source terms decreases with increasing CCN concentrations and larger shape parameters. The relative change is larger for CCN differences than for various shape parameters. However, because the sink terms also show a decrease in magnitude, the net rainfall budget is reduced less than expected due to the reduced source terms.

Finally, our results also showed a dominant cold-rain process for all cases and a stronger relative role of processes via the ice phase for larger shape parameters and increased CCN concentrations. Compared to the respective reference run, the magnitude of latent heat response is quite large and ranges between -19.4% and $+24.5\%$. Consistent with previous work with the ICON model (Barthlott et al., 2022), there is no CCN-induced convection invigoration, with updrafts being less buoyant when the CCN concentration is increased.

Our findings demonstrate that aerosols and the shape parameter of the CDSD are both important for quantitative precipitation forecasting. Especially the concept of combined perturbations based on realistic parameter perturbations in combination with soil moisture heterogeneities can provide

a good ensemble spread. This indicates that the combination of different perturbations used in our study may be suitable for ensemble forecasting and that this method should be evaluated against other sources of uncertainty. The first efforts in this direction were made by Matsunobu et al. (2022), who investigated the relative importance of microphysical uncertainties for cloud and precipitation forecasts implemented in an ICON-D2 ensemble prediction system on different spatial and temporal scales for five real cases in central Europe. Given the overall large impact of uncertainties due to aerosols and the shape parameter identified in this work, the use of a stochastically perturbed parameter (SPP) scheme for these microphysical uncertainties could be beneficial and should be pursued in future work.

Data availability. ICON model output is available on request from the authors.

Author contributions. CB and CK developed the project idea and designed the numerical experiments. AZ performed the numerical simulations. CB and AZ conducted the analyses, TM calculated the convective adjustment timescale, and all contributed to the interpretation of the results. CB wrote the paper, with contributions from all the co-authors.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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