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†Deceased.

Key Points:
• Aerosol changes can cause even larger uncertainties in hail precipitation than initial meteorological perturbations
• Aerosols modify the predictability of hail precipitation, with the highest predictability in moderate polluted environments
• Perturbing the initial meteorological conditions does not qualitatively change how aerosols affect hail and total precipitation

Supporting Information:
Supporting Information may be found in the online version of this article.

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Abstract  There are increasing concerns about the uncertainty aerosols produced in forecasting precipitation, particularly hail. This study provides an assessment of the contribution of aerosols to hail predictability by varying both the cloud condensation nuclei concentration (CCNC) and the initial meteorological conditions based on ensemble runs of 1,200 cloud-resolving simulations. Although the meteorological perturbations produce large uncertainties in both hail and total precipitation, varying CCNC by an order of magnitude causes even larger uncertainties than the meteorological perturbations. Changing CCNC modifies the predictability of hail precipitation, with higher predictability in moderately polluted environments compared with very clean and polluted environments. Perturbing the initial meteorological conditions does not qualitatively change how aerosols affect hail and total precipitation. Constraining the initial meteorological perturbations helps reduce CCNC-caused uncertainty. These findings suggest the importance of considering aerosol effects in severe weather simulations and forecasting.

Plain Language Summary  Hailstorms, a damaging phenomenon found in many areas of the world, are difficult to predict. It is known that hail precipitation intensity and hailstone size are sensitive to small perturbations in meteorological conditions. However, how hailstorms will respond to aerosol change remains largely uncertain. Exploring the uncertainty induced by aerosols in forecasting precipitation, including hail precipitation, is an increasingly hot research topic. In this work, we quantify the uncertainty of hail precipitation by varying both the cloud condensation nuclei concentration (CCNC) and the initial meteorological conditions. A total of 1,200 cloud-resolving simulations of an idealized hailstorm were performed. We find that varying CCNC can cause even larger uncertainties in hail precipitation, including the hail precipitation intensity and maximum hail size, than the meteorological perturbations. These results emphasize the importance of considering aerosol effects in future severe weather forecasting. Thus, this study advances our understanding of hail precipitation predictability and provides practical guidance for forecasting applications.

1. Introduction

Aerosol-cloud interactions can play an important role in regional climate and precipitation, especially via deep convective clouds, but it remains largely uncertain in both weather and climate projections (Fan et al., 2016; Rosenfeld et al., 2008; Tao et al., 2012; Thompson & Eidhammer, 2014). As more and more studies show that aerosols can change deep convective cloud microphysics, dynamics, and precipitation (Chen et al., 2019; Duan et al., 2012; Fan et al., 2016; Tao et al., 2012), there is an increasing concern about the forecast biases caused by aerosols. Hailstorms, a class of severe convective clouds, frequently produce large hailstones that cause significant damage and economic losses across the world (Allen & Allen, 2016; Gagne II et al., 2019; Guan et al., 2014; Li et al., 2018; Ni et al., 2017; Punge & Kunz, 2016). Predicting hailstorms faces various difficulties including considerable uncertainties in the initial meteorological conditions of severe weather events (Flora et al., 2018; Shpund et al., 2019; Tao & Zhang, 2015; Wellmann et al., 2018; Zhang & Tao, 2015).
Traditionally, the forecast community has focused on the impacts and uncertainties attributable to the initial meteorological conditions, from the perspective of the importance of thermodynamic and kinematic factors relevant to both large-scale storm environment and storm initiation in affecting severe storms associated with heavy precipitation, strong wind gusts, and hail (Flora et al., 2018; Li et al., 2019; Schneider et al., 2019; Wellmann et al., 2019; Zhang & Tao, 2013; Zhang et al., 2015, 2016). Small perturbations in the initial meteorological conditions (i.e., the temperature, water vapor, and wind fields) can significantly affect deep convective storms (Li et al., 2019; Wu et al., 2020). The significance of aerosol effects on convective storms and precipitation has often been questioned, and aerosol effects have not been considered much in the forecasting uncertainty of storms and their associated weather hazards like hail (Morrison, 2012).

The uncertainties in models have been quantified by operating advanced ensemble simulations to representing various sources of initial meteorological conditions since the development of supercomputers (Flora et al., 2018; Labriola, Snook, Jung, & Xue, 2019; Li et al., 2019; Luo et al., 2018; Meng et al., 2019; Tao & Zhang, 2014; Wellmann et al., 2018; Weyn & Durran, 2017; Zhang & Tao, 2013). The predictability of hail can be limited by the uncertainty in the atmospheric state (Li et al., 2019; Wellmann et al., 2018), attributable to various initial conditions including aerosols. Since the majority of studies on aerosol-cloud interactions neither employed an ensemble approach nor considered the variability of meteorological conditions (Fan et al., 2012, 2018; Khain et al., 2005, 2015; Rosenfeld et al., 2014; van den Heever et al., 2011), it is still an open question what aerosol impacts would look like with considerations of the uncertainties of meteorological perturbations. A recent study did a small meteorological ensemble (10 members) and showed that aerosol-induced changes are statistically significant for cloud droplet number concentrations, cell number and size, outgoing shortwave radiation, and precipitation efficiency (Miltenberger et al., 2018). Quantifying the uncertainty caused by aerosols under perturbed atmospheric environments is important to determine the role of aerosol-cloud interactions in climate and weather prediction.

To address the abovementioned knowledge gap, in this study, we assess the uncertainties in predicting precipitation, particularly hail precipitation, by varying cloud condensation nuclei (CCN) concentration (CCNC) with a concurrent variation of initial thermodynamic (i.e., potential temperature and water vapor mixing ratio) and kinematic (i.e., U- and V-wind components) perturbations. An ensemble approach is employed and cloud-resolving simulations of an idealized hailstorm using the Weather Research and Forecasting (WRF) model are carried out to quantify the uncertainties of hail precipitation.

2. Ensemble Simulation Design

The simulated hailstorm occurred at Ordos City in the Inner Mongolia Autonomous Region of China and started at 0600 UTC 30 June 2013, lasting about 2 h, with a maximum hailstone size of 6 mm observed at the meteorological station of No. 53543 and egg-size hailstones reported on social media. It was associated with a trough of low pressure and a pre-storm environment favorable for deep moist convection, with a convective available potential energy of about 1,800 J·kg\(^{-1}\). The same case was simulated in Li et al. (2017, 2019) in an idealized model setup, with a thermal bubble initialization default in WRF3.7.1 (Skamarock et al., 2008). The configurations of the model follow the method described in Li et al. (2017) and the method of the initial meteorological perturbations follows what was used in Li et al. (2019) (Text S1). The initial meteorological perturbations here mean the changes to the initial vertical profiles of the environmental kinematic (wind) and thermodynamic (temperature and water vapor) fields (Figure S1). The initial model environment is horizontally homogeneous, and the thermal bubble initialization is kept the same among the sensitivity tests. The simulations were run at the 500-m horizontal grid spacing with 51 vertical levels and with the standard release of the NSSL two-moment microphysics scheme in WRF3.7.1 (Labriola, Snook, Xue, & Thomas, 2019; Mansell & Ziegler, 2013; Mansell et al., 2010). The scheme predicts mass and number mixing ratios of two liquid (cloud droplets and rain) and four ice hydrometeor categories (ice crystals, snow, graupel, and hail).

The control ensemble simulation, named CCN700-ALL in this paper is the same as the control ensemble of EC_All in Li et al. (2019), in which ALL refer to all meteorological perturbations including both the thermodynamic and kinematic fields. The 50 perturbed meteorology profiles for the ensemble run CCN700-ALL were interpolated from the 0-h forecast European Center for Medium-Range Weather Forecasting
(ECMWF) operational ensemble. Five additional sensitivity ensemble experiments were performed by varying CCNC from 100 to 3,000 mg $^{-1}$ (shown from the $x$-coordinate in Figure 1), representing conditions changing from clean to polluted air. In total, the control ensemble group ALL contains 300 runs (6 CCNC cases multiplied by 50 members, consisting of CCN100-ALL, CCN300-ALL, CCN500-ALL, CCN700-ALL, CCN1000-ALL, and CCN3000-ALL).

To assess the main factors contributing to the uncertainties and predictability in hail and precipitation, as well as understand how the CCNC effects on precipitation change with different perturbations in meteorology, three additional ensemble groups (shown along the $y$-coordinate of Figure 1) for each CCNC ensemble were modeled. Two of them concern perturbations in the thermodynamic conditions (i.e., the potential temperature and water vapor mixing ratio; referred to as TQ) and the kinematic conditions (i.e., the U and V components of winds; referred to as UV). Following previous literature (Li et al., 2019), both combined and isolated thermodynamic and kinematic perturbations were generated from the pre-storm environment from the ECMWF operational 50-member ensemble (Text S1). To examine the intrinsic predictability of hail and total precipitation, another ensemble group named 10%ALL was performed with both the thermodynamic and kinematic perturbations reduced to 10% of their original magnitudes in ALL. In total, 24 groups of ensembles, consisting of $50 \times 6 \times 4$ runs in a total of 1,200 simulations, were configured. The uncertainty is represented by the ensemble spread, that is, the standard deviation of the 50 members in each ensemble group. The predictability is revealed by the ratio of signal (i.e., the ensemble mean) to noise (i.e., the ensemble spread) (Zhang & Kirtman, 2019).

3. Results

3.1. Effects of Aerosols on Hail and Total Precipitation

The ensemble mean shows a nonmonotonic response of hail precipitation rate to CCNC variation in the ensemble group ALL (Figure 2a), which shows an optimal CCNC at around 300 mg $^{-1}$, similar to Li et al. (2017) which used a single set of simulations without ensembles. The uncertainty of the hail precipitation rate (i.e., the ensemble spread in Figure 2d), increases with the ensemble mean values. The ensemble spreads of the hail precipitation rates are generally comparable to the ensemble means for each CCNC setting (Figures 2a and 2d), indicating that the meteorological perturbations can cause large uncertainties. The difference between the peak and valley of the ensemble mean of the maximum hail precipitation rate due to CCN variation (Figure 2a) is larger than the maximum ensemble spread values produced by the initial meteorological perturbations shown in Figure 2d. This means that changing CCNC can cause much larger uncertainties.
compared to initial perturbations in the thermodynamic and kinematic factors. The total precipitation rate is more than 20 times larger than the hail precipitation rate (Figures 2a and 2b). Interestingly, there is a monotonic decrease trend in the ensemble means with the increase of CCNC (Figure 2b), so does the ensemble spread in Figure 2e. However, the ensemble spreads are much lower in magnitude than the ensemble means, representing a smaller uncertainty (i.e., higher predictability) in the total precipitation rate than the hail precipitation rate.

Like the hail precipitation rate, the maximum hail size also follows a nonmonotonic response to increasing CCNC (Figure 2c). The ensemble mean increases from about 22 mm in CCN100 to ∼28 mm in CCN300 and CCN500, classified as severe hail (>25 mm), then decreases to ∼18 mm in CCN3000. Changing CCNC increases the uncertainty of hail size indicating by ensemble spreads, which increase from ∼5 mm in CCN100 to ∼8 mm in CCN3000 (Figure 2f). The largest difference in maximum hail size caused by CCNC is about 10 mm, larger than the ensemble spread (Figure 2f) that represents the uncertainties produced by the initial meteorological perturbations. This indicates that aerosol variations can also cause larger uncertainties in hail size than the initial meteorological perturbations.

To assess the predictability more quantitatively, the ratio of ensemble means to ensemble spreads (i.e., the signal-to-noise ratio) is plotted (last row of Figure 2). A large signal-to-noise ratio means higher predictability and lower uncertainty. The values for the hail precipitation rate (Figure 2g) are small, indicating low predictability. They are a few times lower than those for the total precipitation rate (Figure 2h), suggesting that the hail precipitation rate may have much lower predictability (i.e., a larger uncertainty in prediction).
than the total precipitation rate. In other words, the former is more sensitive to the initial meteorological conditions. Changing CCNC varies the signal-to-noise ratio from 0.7 to 1.4 for the hail precipitation rate and from 1.2 to 4.1 for the total precipitation rate, suggesting CCNC notably affects the predictability of both. The maximum hail size has signal-to-noise ratios comparable to the total precipitation rate but much larger than the hail precipitation rate, indicating that the maximum hail size is less sensitive to the initial meteorological perturbations than the hail precipitation rate.

### 3.2. Aerosol Effects With Different Meteorological Perturbations

In all four meteorological settings, increasing CCNC leads to a nonmonotonic response of the peak value ensemble mean for hail properties, but a decreasing response of the total precipitation rate (Figure S2). This suggests that varying the initial meteorological conditions does not qualitatively change the aerosol effects on hail and total precipitation. As expected, the ensemble spreads in the hail and total precipitation produced by CCNC decrease with the reduced meteorological perturbation (i.e., from ALL, TQ, UV, to 10%ALL). In general, the thermodynamic perturbation produces larger ensemble spreads than the kinematic perturbation in the hail and total precipitation rates (Figure S2), showing that the uncertainties are more sensitive to thermodynamic perturbation than kinematic perturbation in all aerosol settings. The ensemble spreads in hail and total precipitation rates are changed significantly by CCNC (Figure S2), showing that the uncertainties in these quantities produced by initial meteorological perturbations can be effectively modified by CCNC. The CCNC variation leads to even larger uncertainties in hail and total precipitation rates than initial thermodynamic and kinematic perturbations, shown also in Figure S2 (i.e., the CCNC variation causes a larger difference in the ensemble spread as shown from the peaks and valleys in ALL, TQ, and UV).

The ratio of the peak of the domain-averaged hail precipitation rate for every ensemble group to the control ensemble group CCN700-ALL is plotted in Figure 3, for both the ensemble mean and spread, to visually display comparisons of CCNC effects to the meteorological perturbation effects. Decreasing CCNC from 700 to 300 mg $^{-1}$ produces the largest increase (over 3.0) in the ensemble mean of hail precipitation rate,
while increasing CNCC to 3,000 mg\(^{-1}\) produces the largest decrease (below 0.4) in all four meteorological perturbation ensembles (Figure 3a). As discussed above, the ensemble mean of total precipitation rate monotonically decreases as CCNC increases, which is also consistent among all four meteorological perturbation groups, differing from the hail precipitation rate. However, similar to the hail precipitation rate, the CCN effect is more significant in relatively clean environments (<700 mg\(^{-1}\)) compared to relatively polluted environments (>700 mg\(^{-1}\)) (Figure 3c).

Compared to CCN700-ALL (Figure 3b), the uncertainties (i.e., the ensemble spreads) in the hail precipitation rate can be increased by over 2.0 times when the CCNC is reduced to relatively clean conditions. However, they can be decreased by over 0.6 when increasing to the polluted conditions in both ensemble groups of ALL and TQ. This suggests in very clean conditions hail precipitation rate is more sensitive to meteorological perturbations compared with the very polluted conditions. The ratio range between the cleanest and the most polluted ensembles can be as large as 1.8 (Figure 3b), larger than the range in CCN700-ALL with varied meteorological conditions, corroborating a larger uncertainty in hail predictability from CCNC variation than the meteorological perturbations. The uncertainties in UV and 10%ALL have the largest reductions in either very clean or very polluted environments. This shows that reducing uncertainties in the initial meteorological conditions, especially reducing the thermodynamics uncertainty, could lead to higher predictability in hail precipitation, with the reduction most evident in the cleanest and most polluted environments. Similar results can be seen in the total precipitation rate (Figure 3d), but with a smaller magnitude of uncertainties, corroborating that CCN effects produce larger uncertainties in the hail precipitation than the total precipitation.

Reducing the initial meteorological perturbation magnitudes to 10% of their original magnitudes allows us to examine the intrinsic predictability under an assumption of nearly perfect knowledge of the atmospheric state and a nearly perfect forecast model. Unsurprisingly, reducing the initial meteorological perturbation magnitude causes less variation in the ensemble spreads of hail and total precipitation and the reduced CCNC effects (Figures S2b and S2d). The ensemble spreads in both hail and total precipitation rates in 10%ALL are reduced to 10%–20% of them in ALL (Figures S3a and S3b), suggesting their uncertainty can be reduced drastically by constraining the initial meteorological conditions. Interestingly, the uncertainty trend from the low to high CCNC (Figures S2b and S2d) is not much changed when the initial meteorological perturbation magnitude is reduced to 10% (Figure 3); thus, the uncertainty caused by the aerosol effect is not influenced by the initial meteorological perturbations.

### 3.3. Updraft Velocity, Latent Heating, and Microphysics

To explain the CCNC effects and the uncertainties caused by CCNC under various initial meteorological perturbations, we examined the corresponding cloud dynamics (updraft velocity) (Figure 4a), latent heating rate (Figures 4b–4d), and microphysics (Figures S4 and S5). The updraft velocity and latent heating rates were calculated for the mean of the top 25th percentiles to alleviate the influences of the spikes from ensembles. The responses of updraft velocity to CCNC are consistent among ALL, TQ, UV, and 10%ALL. That is, the updraft velocity increases with CCNC until reaching 500 mg\(^{-1}\) and then slightly decreases with further increases of CCNC (Figure 4a), a common feature in CCN effects (Fan et al., 2009; Li et al., 2008; Wang, 2005). The enhanced updraft velocity by increasing CCNC before reaching the optimal CCNC value should be mainly due to the enhanced latent heating from condensation, since freezing and deposition latent heating is smaller than the condensational heating and the increase is limited as well (Figures 4b–4d).

Beyond the optimal CCNC value, a further increase slightly decreases updraft velocity (Figure 4a), which could be related to a decreased latent heating from the reduced droplet freezing (Figure 4c) and enhanced evaporative cooling. Although the deposition heating increases drastically with a further increase in CCNC after the optimum CCNC (Figure 4d), it does not lead to a further increase in updraft velocity (Figure 4a). This suggests that increases in the depositional heating may not have a large effect on convection, which is aligned with the finding from Fan et al. (2018) and Lebo (2018) showing increasing latent heating at the upper-levels (via deposition) is not effective in enhancing vertical velocity. The large increase in the depositional heating in the high CCNC conditions is due to a great increase in the deposition to snow (Figures 4d, S4g, and S5g). From Figures 4b–4d, we also see that latent heating is much more sensitive to the CCNC changes than the initial meteorological perturbations.
The nonmonotonic updraft intensity explains the similarly nonmonotonic response of the graupel and hail mass in clouds (Figure S4), leading to the nonmonotonic responses of surface hail precipitation rates to the increase of CCNC. More specifically, before reaching the optimal CCNC, the increased vertical velocity enhances hail formation and growth through increasing supercooled liquid, thus enhancing riming. However, when CCNC further increases and becomes too high, the supercooled droplets become too small in size, making riming very inefficient with a low collision efficiency. This leads to decreased graupel and hail mass as CCNC further increases beyond its optimal value. The graupel precipitation on the surface is decreased because of less large graupel aloft and enhanced melting since graupel sizes are getting smaller in the polluted conditions (Figures S6a and S6c).

In the CCN effect on total precipitation, increased CCNC produces a larger mass of cloud but a smaller mass of rain due to the reduced auto-conversion rate of small cloud drops into rain droplets (Figures S2 and S5), contributing to the monotonical decrease in total precipitation in all of the initial meteorological perturbation settings (Figure 2). In addition, the monotonical decrease in total ice precipitating particles (graupel plus hail) is another factor, mainly due to a large decrease in graupel precipitation (Figures S4 and S6). Cloud ice and snow monotonically increase as CCNC increases (Figures S4 and S5) due to enhanced droplet freezing and depositional growth, consistent with the previous literature studies (Fan et al., 2007; Khain et al., 2005; Li et al., 2008).

Aerosol effects on all six hydrometeors are not strongly influenced by the meteorological perturbations (Figure S5); thus, the consistent aerosol effects on hail and total precipitation are seen across all of the ICN effects.
meteorological settings. Varying CCNC generally produces larger uncertainties in all hydrometeors than varying the initial meteorological perturbations (ALL, TQ, and UV) (Figure S5). For example, the ensemble spread for cloud mass among ALL, TQ, and UV varies from about $0.8 \times 10^8$ to $1.8 \times 10^8$ kg in CCNC700, while the ensemble spread in ALL due to the CCNC changes varies in a larger range from $0.6 \times 10^8$ to $2.5 \times 10^8$ kg (a similar variation in TQ). Even in UV, the ensemble spread from the CCNC changes goes from $0.2 \times 10^8$ to $1.0 \times 10^8$ kg, comparable to the range of $(0.8–1.8) \times 10^8$ kg obtained by varying the initial meteorological perturbations. The uncertainties between ALL and TQ are similar and much larger than in UV, suggesting that the thermodynamic perturbation dominates the uncertainties in the cloud microphysics properties, and adding the dynamic perturbation does not notably increase the uncertainties. These above-mentioned features in the uncertainties of cloud microphysical properties explain the similar results in the uncertainties of hail and total precipitation discussed in earlier sections.

It is worth mentioning that for cloud mass the signal-to-noise ratios are much larger than those for ice and snow mass, and those for rain are larger than those for graupel and hail (Figure S7). This suggests that the warm-phase hydrometeors have smaller uncertainties than the ice-related hydrometeors, explaining the larger uncertainty (lower predictability) in hail precipitation compared with the total precipitation shown in Figure 2. With the reduced initial meteorological perturbation (10%ALL), the uncertainties in all hydrometeor mass are much reduced compared with ALL (Figure S5), supporting the overall reduced uncertainties in hail and total precipitation.

4. Conclusions

Based on 24 ensemble groups consisting of 1,200 runs, with the perturbed initial meteorological conditions and aerosol settings, we find that varying CCNC by an order of magnitude (from 100 to 3,000 mg$^{-1}$) produces a notable effect on the predictability of the hail precipitation (including rate and maximum hail size) and total precipitation. The initial meteorological perturbations produce large uncertainties. However, varying the CCNC can cause even larger uncertainties than the meteorological perturbations in the hail precipitation, total precipitation, and maximum hail size.

Hail precipitation exhibits a non-monotonic response to the increase of CCNC, but total precipitation demonstrates a monotonic response in both ensemble mean and ensemble spread. In relatively clean environments, a large increase in the updraft velocity by increasing CCNC, which is mainly due to the enhanced condensational latent heating, promotes graupel and hail formation and growth because of the increased supercooled droplets. Further increasing CCNC beyond the optimal CCN value leads to very small supercooled droplets, suppressing the riming and freezing efficiencies, thus reducing graupel and hail formation and growth. The monotonic decrease in the total precipitation by increasing CCNC is attributed to the suppressed warm rain process and decreased graupel precipitation.

Aerosol effects on both hail and total precipitation are found to be robust under various meteorological perturbations. Thus, varying the initial meteorological conditions does not qualitatively change the aerosol effects. Aerosols modify the predictability of hail precipitation, with the highest predictability in moderate polluted environments. The hail precipitation rate is more sensitive to meteorological perturbations in very clean conditions compared with very polluted conditions.

Constraining the initial meteorological conditions (such as reduced to 10% of the original perturbations) reduces the uncertainties and improves the practical predictability of hail and total precipitation. Overall, the hail precipitation rate has a larger uncertainty (lower predictability) than the total precipitation rate because of the large uncertainties in the precipitating large ice hydrometeors (graupel and hail). The results of this study have an important implication to severe weather simulations and forecasting since aerosol effects are generally neglected. It is noted the this is a single case study and more real-case studies are needed to test if the results are applied to other severe convective storms with very different thermodynamics and kinematics. In addition, the results may have some uncertainties particularly from cloud physics parameterizations and the idealized thermal bubble convective initiation.
Data Availability Statement

All data for this study come from WRF3.7.1 model (https://doi.org/10.5065/D6MK6B4K) simulations and are properly cited and referred to in the reference list to support reproducibility with the details in Ensemble Simulation Design. All the input-sounding data for reproduction of the ensembles and the original data for the figures in this study can be found at Li (2021) (DOI: https://doi.org/10.17632/jr7pzbdbkb.1). Data analysis and visualizations in this paper are created by the NCAR Command Language (NCL) (Version 6.6.2), which can be accessed via http://dx.doi.org/10.5065/D6WD3XH5.

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