Aerosol-Cloud-Precipitation Interactions in WRF Model: Sensitivity to Autoconversion Parameterization

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ABSTRACT

Cloud-to-rain autoconversion process is an important player in aerosol loading, cloud morphology, and precipitation variations because it can modulate cloud microphysical characteristics depending on the participation of aerosols, and affects the spatio-temporal distribution and total amount of precipitation. By applying the Kessler, the Khairoutdinov-Kogan (KK), and the Dispersion autoconversion parameterization schemes in a set of sensitivity experiments, the indirect effects of aerosols on clouds and precipitation are investigated for a deep convective cloud system in Beijing under various aerosol concentration backgrounds from 50 to 10000 cm^{-3}. Numerical experiments show that aerosol-induced precipitation change is strongly dependent on autoconversion parameterization schemes. For the Kessler scheme, the average cumulative precipitation is enhanced slightly with increasing aerosols, whereas surface precipitation is reduced significantly with increasing aerosols for the KK scheme. Moreover, precipitation varies non-monotonically for the Dispersion scheme, increasing with aerosols at lower concentrations and decreasing at higher concentrations. These different trends of aerosol-induced precipitation change are mainly ascribed to differences in rain water content under these three autoconversion parameterization schemes. Therefore, this study suggests that accurate parameterization of cloud microphysical processes, particularly the cloud-to-rain autoconversion process, is needed for improving the scientific understanding of aerosol-cloud-precipitation interactions.

Key words: autoconversion parameterization, aerosol-cloud-precipitation interactions, numerical simulation

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1. Introduction

Anthropogenic aerosols acting as cloud condensation nuclei (CCN) or ice nuclei (IN) can alter the microphysical properties of liquid and ice clouds, as well as local and global precipitation (Ramanathan et al., 2001). Due to the complexity of the involved physical processes involving aerosol characteristics and atmospheric environment factors, aerosol-cloud-precipitation interaction has attracted considerable attention in studies based on ground observations, satellite retrievals, and numerical modeling (Zhang, 2007; Levin and Cotton, 2009; Tao et al., 2012; Han et al., 2014).

Cloud-to-rain autoconversion represents a key microphysical process whereby rain drops are formed by collision-coalescence processes of cloud droplets. This microphysical process is an important player in aerosol loading, cloud morphology, and precipitation processes because aerosol-induced changes in cloud microphysics can affect the spatio-temporal variations of precipitation in addition to its onset and amount (Albrecht,

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1989). A series of parameterization schemes describing the autoconversion process have been proposed during the past several decades (e.g., Kessler, 1969; Berry and Reinhardt, 1974; Sundqvist et al., 1989; Beheng, 1994; Khairoutdinov and Kogan, 2000; Liu and Daum, 2004; Liu et al., 2005; Xie and Liu, 2009), most of which have been successively applied to multi-scale numerical atmospheric models. These autoconversion parameterization schemes can be roughly classified into three categories. The first category includes only the cloud water content without aerosol effects, e.g., the Kessler scheme (Kessler, 1969). The second is related to both the cloud water content and the droplet number concentration that can represent the indirect effect of aerosols, e.g., the Khairoutdinov-Kogan (KK) scheme (Khairoutdinov and Kogan, 2000). The third includes cloud droplet spectral dispersion, the cloud water content, and the droplet number concentration, which can be used to investigate the aerosol effects with spectral dispersion influence, e.g., the Dispersion scheme proposed by Liu and Daum (2004) and Liu et al. (2005). To reveal the differences between these parameterization schemes, we couple the Kessler, KK, and Dispersion schemes respectively with the Morrison bulk microphysics scheme of the Weather Research and Forecast (WRF) model for investigating the impacts of aerosols on clouds and precipitation in a deep convective system that occured on 31 March 2005 in Beijing.

The main contents of this paper are organized as follows. Section 2 introduces autoconversion parameterization schemes, including the Kessler, KK, and Dispersion, as well as the WRF model with the Morrison bulk microphysics scheme. In Section 3, we present the main results associated with cloud microphysical properties and surface precipitation from numerical simulations incorporating the above schemes. In Section 4, we conclude our paper with a summary.

2. Autoconversion parameterization and the WRF model

2.1 Autoconversion parameterization

The autoconversion process of cloud droplets to rain drops represents a key microphysical process, which governs the onset of precipitation in warm clouds and affects the precipitation distribution and amount. The Kessler scheme assumes that the autoconversion rate increases with an increase in cloud water content, although it is zero for some cloud water content values below the threshold value $L_{\rm c0}$, i.e., the autoconversion process of cloud to rain does not occur below $L_{\rm c0}$ (Kessler, 1969). This microphysics scheme has been widely used in cloud-related modeling studies because of its simplicity. The formula of the Kessler scheme is expressed as

$$P_{\rm K} = \alpha(L_{\rm c} - L_{\rm c0}){\rm H}(L_{\rm c} - L_{\rm c0}). \tag{1}$$

The unit of autoconversion rate $P_{\rm K}$ is g kg^{-1} s^{-1}. Here α is a tuning constant, ${\rm H}(L_{\rm c} - L_{\rm c0})$ is the Heaviside step function, and $L_{\rm c}$ is the cloud water content (g kg^{-1}). The values for the threshold cloud water content $L_{\rm c0}$ are rather arbitrary. Typically, for deep cumulus convection, we choose $\alpha = 10^{-3}$ s^{-1} and $L_{\rm c0} = 1$ g kg^{-1} according to Wang (2005).

The KK scheme states that the autoconversion rate increases with increasing cloud water content and decreases with increasing droplet number concentration. This is determined from many numerical experiments with a drop spectrum resolving microphysical model (Khairoutdinov and Kogan, 2000). The corresponding formula is given by

$$P_{\rm KK} = 1350 L_{\rm c}^{2.47} N_{\rm c}^{-1.79}, \tag{2}$$

where the autoconversion rate $P_{\rm KK}$ is in kg kg^{-1} s^{-1}, and the units of $L_{\rm c}$ and $N_{\rm c}$ (cloud droplet number concentration) are kg kg^{-1} and cm^{-3}, respectively. Note that this autoconversion parameterization scheme is used in general circulation models such as ECHAM5 (Lohmann et al., 2007), CAM3, and CAM5 (Morrison and Gettelman, 2008).

The Dispersion scheme assumes that the autoconversion rate is related to the cloud water content, droplet number concentration, and cloud droplet spectral dispersion. This scheme was proposed by Liu and Daum (2004) and Liu et al. (2005), and has been coupled into the WRF model (Xie and Liu, 2011; Xie et al., 2013). The autoconversion parameterization is written as

$$\begin{aligned} &P_{\rm D} = P_0 T, \\ &P_0 = 1.1 \times 10^{10} \Big[\frac{(1+3\varepsilon^2)(1+4\varepsilon^2)(1+5\varepsilon^2)}{(1+\varepsilon^2)(1+2\varepsilon^2)} \\ &\qquad \cdot N_{\rm c}^{-1} L_{\rm c}^3\Big], \qquad (3) \\ &T = \frac{1}{2}(x_{\rm c}^2 + 2x_{\rm c} + 2)(1+x_{\rm c}){\rm e}^{-2x_{\rm c}}. \end{aligned}$$

Here, $P_{\rm D}$ (g cm^{-3} s^{-1}) is the cloud-to-rain autoconversion rate; P_0 (g cm^{-3} s^{-1}) and T (dimensionless) represent the rate function and threshold function, respectively (Liu and Daum, 2004; Xie and Liu, 2009). The microphysical variables $N_{\rm c}$ and $L_{\rm c}$ are the cloud droplet number concentration (cm^{-3}) and cloud water content (g cm^{-3}), and $x_{\rm c}$ has an analytic formula of $x_{\rm c} = 9.7 \times 10^{-17} N_{\rm c}^{3/2} L_{\rm c}^{-2}$. The cloud droplet spectral dispersion ε is defined as the ratio of standard deviation and mean radius of the cloud droplet size distribution, which can be described by the various functions of cloud droplet number concentration (Xie and Liu, 2013). Here, we adopt the formula with $\varepsilon = 0.0005714N_{\rm c}+0.271$ (Martin et al., 1994), where the cloud droplet spectral dispersion is a linear function of cloud droplet number concentration.

2.2 Model and design of numerical experiments

The WRF model is a state-of-the-art mesoscale numerical weather prediction system used for both operational forecasting and atmospheric research; version 2.2 was released in December 2006 (Skamarock et al., 2005). The WRF model offers a wide range of meteorological applications across scales ranging from meters to thousands of kilometers. A two-moment bulk cloud microphysics scheme, namely, version 2.0 of the Morrison bulk microphysics scheme proposed by Morrison et al. (2005), is used here. As mentioned by Xie et al. (2013), this microphysics scheme is able to predict the cloud droplet number concentration $N_{\rm c}$, which differs from the standard released WRF model that uses a fixed value of $N_{\rm c} = 250$ cm^{-3}. In this bulk microphysics scheme, the number concentration and water content of five classes of hydrometeors are predicted, including cloud droplets, rain drops, ice crystals, snow, and graupel. The autoconversion parameterization used in this bulk microphysics scheme is the KK scheme.

To examine the differences between the various autoconversion parameterization schemes, we also coupled the Kessler and Dispersion schemes into the Morrison bulk microphysics scheme in the WRF model. Additionally, aerosols in this study serve only as CCN associated with warm clouds. Although several studies indicate that aerosols have non-negligible impacts on mixed-phase and ice-phase cloud properties by acting as ice nuclei (e.g., van den Heever et al., 2006), the heterogeneous ice nuclei concentration does not vary between different aerosol concentration backgrounds in the Morrison bulk microphysics scheme.

All the simulations in this study are performed over a domain with grids at a 1-km grid spacing in addition to 41 vertical sigma levels up to 20 km in altitude. The model was integrated for 3 h with a 6-s time step, and the results were output every 5 min. Here, we use periodic boundary conditions for the horizontal boundaries. The initial thermodynamic conditions were derived from the sounding data for simulations of the convective cloud system that occurred on 31 March 2005 in Beijing. This convective cloud system revealed moderate instability in the atmosphere, showing convective available potential energy (CAPE) of 1133 J kg^{-1} integrated from the surface, and convection inhibition (CIN) of approximately zero. The mixing ratio of water vapor had a maximum value of 9 g kg^{-1}, which decreased continuously with increasing vertical height, and the corresponding surface temperature was nearly 31℃. The wind shear of the two components (u and v) of the wind fields was relatively weak. The details of this thermodynamic sounding have been reported by Xie et al. (2013).

The activation of cloud droplet was calculated by an empirical formula (Pruppacher and Klett, 1997):

$$N_{\rm ccn} = C_0 S^k, \qquad (4)$$

where $N_{\rm ccn}$ is the number concentration of activated CCN, and thus the number concentration of newly formed cloud droplets under a given supersaturation ratio S (in percent here). C_0 and k are constants depending on the chemical composition and physical properties of the aerosols; k is given as 0.7, as suggested by Wang (2005), and C_0 is the activated CCN number concentration at 1.0% supersaturation by definition. For simplicity, this initial CCN number concentration at 1.0% supersaturation (hereinafter, CCN0) is used to represent the aerosol distribution in each numerical experiment according to Li et al. (2008). In the present study, CCN0 was set as 50, 100, 200, 300, 500, 1000, 2000, 3000, 5000, and 10000 cm^{-3} to represent the increasing aerosol concentration, and we performed the experiments by using the Kessler, KK, and Dispersion schemes with increasing CCN0. Here, the reference case takes the results of the Dispersion scheme with CCN0 = 50 cm^{-3}.

3. Results

3.1 Case description

Characteristics of the deep convective cloud system revealed by the reference simulation are given in Fig. 1, which shows the domain-maximum vertical velocity and rain rate as functions of time. The domain-maximum value is defined as the maximum value of those at all the grids covering the entire domain under a given time, and the domain average value is defined as the average value of all the grids for the entire domain during the 3-h integration period. Figure 1a shows the dynamic properties. The domain-maximum vertical velocity had a rapid increase over time, before reaching the maximum value (nearly 27 m s^{-1}) at 0.5 h. The maximum vertical velocity thereafter began to decline, becoming very small and close to zero after 1.5 h. Correspondingly, Fig. 1b shows the surface precipitation, which mainly occurred during the first 1.5 h of the simulation. Compared with the maximum vertical velocity, the rain rate reached its maximum value (nearly 0.19 mm h^{-1}) relatively late at 1.25 h.

Additionally, the aerosol effects on the domain-maximum vertical velocity were insignificant (figures omitted). These results are similar to those of several previous studies that used the Morrison bulk microphysics scheme (Morrison, 2012; Xie et al., 2013). However, several bin microphysics models have demonstrated stronger convection induced by more latent heat release with increased aerosol loading (Khain et al., 2005; Lebo and Seinfeld, 2011; Tao et al., 2012). Regarding to the aerosol effects on clouds and precipitation, we present the results in the following subsections for the three autoconversion parameterization schemes.

3.2 Aerosol effects on cloud microphysical properties

The dependence of cloud microphysical properties on various CCN number concentrations is presented in Fig. 2 for the Kessler, KK, and Dispersion schemes. Figure 2a shows that the cloud droplet number concentration increased markedly with the CCN number concentration. With increasing CCN number concentration, more aerosols are activated into cloud droplets,

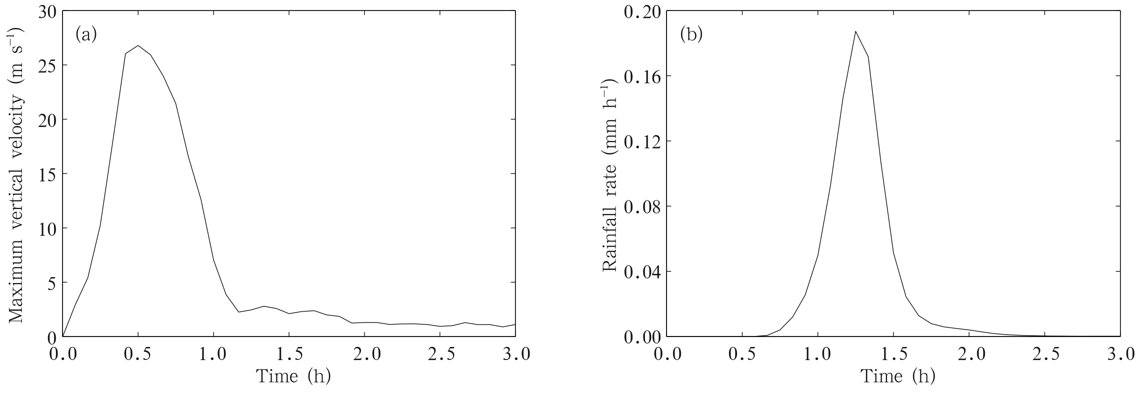

Fig. 1. Variations with time of (a) the simulated domain-maximum vertical velocity (m s^{-1}) and (b) corresponding rainfall rate (mm h^{-1}) for the reference case.

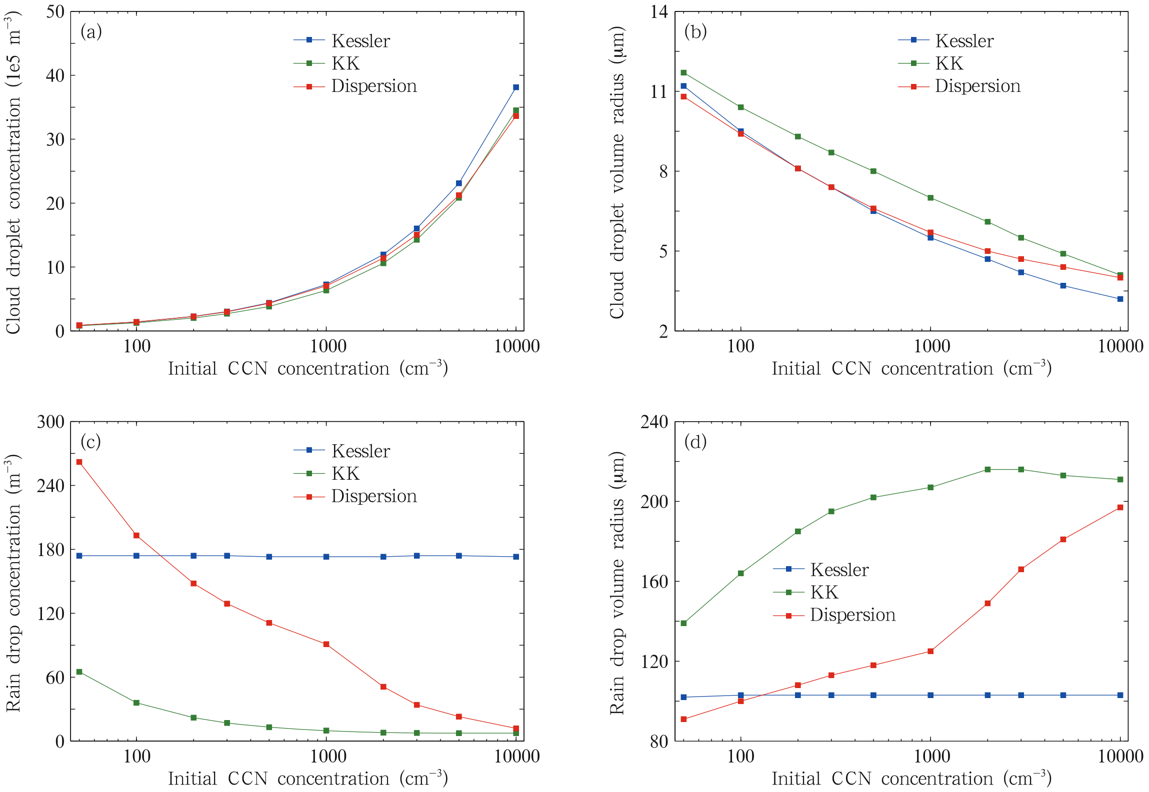

Fig. 2. Simulated (a) number concentration of cloud droplet, (b) mean volume radius of cloud droplet, (c) number concentration of rain drop, and (d) mean volume radius of rain drop, derived from the domain average values within 3 h of integration for the three autoconversion parameterization schemes under various initial CCN concentrations.

thereby enhancing the cloud droplet number concentration (e.g., Kaufman and Nakajima, 1993). Figure 2b shows that the mean volume radius of cloud droplets decreased with increasing CCN number concentration, suggesting that a relatively large number of cloud droplets were competing for the fixed amount of water vapor. Figures 2a and 2b indicate that the Kessler, KK, and Dispersion schemes only altered the properties of cloud droplets slightly. This is because the activation scheme of aerosols into cloud droplets is exactly the same as described by Eq. (4) in all the three schemes.

In comparison with the cloud droplets, changes in rain drops with increasing CCN number concentration are more complex for the three autoconversion schemes (Figs. 2c and 2d). The Kessler scheme showed insignificant variation in the number concentration and mean volume radius of rain drops with CCN number concentration. This is because the Kessler scheme cannot represent the indirect effect of aerosols, and the autoconversion rate is unrelated to the cloud droplet number concentration. The decreasing (increasing) trends of rain drop concentration (rain drop mean volume radius) were consistent for the KK and Dispersion schemes, displaying the aerosol indirect effects. The number concentration of rain drops was reduced from clean to polluted aerosol backgrounds. The enhanced activation of aerosol particles to cloud droplets can form a larger number of droplets with smaller sizes or radii, leading to lower efficiency of cloud-to-rain autoconversion process. The mean volume radius of rain drops can be increased with increasing aerosol particles. In contrast to the autoconversion process, a relatively more efficient accretion growth occurs due to higher cloud water content in polluted backgrounds, which can eventually result in larger sizes of rain drops (Xie et al., 2013). Higher aerosol loading can result in an increase in the radii or sizes of rain drops, which is in good agreement with the results of several previous investigations (Cheng et al., 2007; Li et al., 2008; Lim and Hong, 2010; Xie et al., 2013).

Figure 3 shows the domain-averaged water content of hydrometeors within 3 h of integration under various initial CCN number concentrations with the three autoconversion parameterization schemes for cloud, rain, and ice species. The water content of ice species is the sum of the content of ice, snow, and graupel. For the Kessler scheme, aerosol loading slightly altered all of the hydrometeor species. For the KK scheme, the cloud water content increased and the rain water content decreased with increasing CCN number concentration (Figs. 3a and 3b). More and smaller cloud droplets induced by aerosols can hinder the autoconversion process of cloud droplets into rain drops, resulting in higher cloud water content but lower rain water content (Xie et al., 2013). The water content of ice species increased with CCN number concentration (Fig. 3c). More cloud droplets induced by aerosols can be transported and frozen into cold cloud regimes to enhance the processes of the ice phase and thus to form more ice hydrometeor species.

Note that the Dispersion scheme differs from the KK scheme. The former considers the influence of cloud droplet spectral dispersion, which was parameterized as the increasing function of cloud droplet number concentration as described in Section 2. Therefore, the increase in cloud droplet spectral dispersion can enhance the autoconversion process, which compensates for part of the decreasing autoconversion efficiency induced by aerosols. As shown in Fig. 3, the increasing or decreasing trends in the hydrometeor water content of the Dispersion scheme with increasing CCN number concentration are essentially consistent with those in the KK scheme. However, a large difference exists between the values of the hydrometeor water content for these two autoconversion schemes. The cloud water content is lower, and the rain water

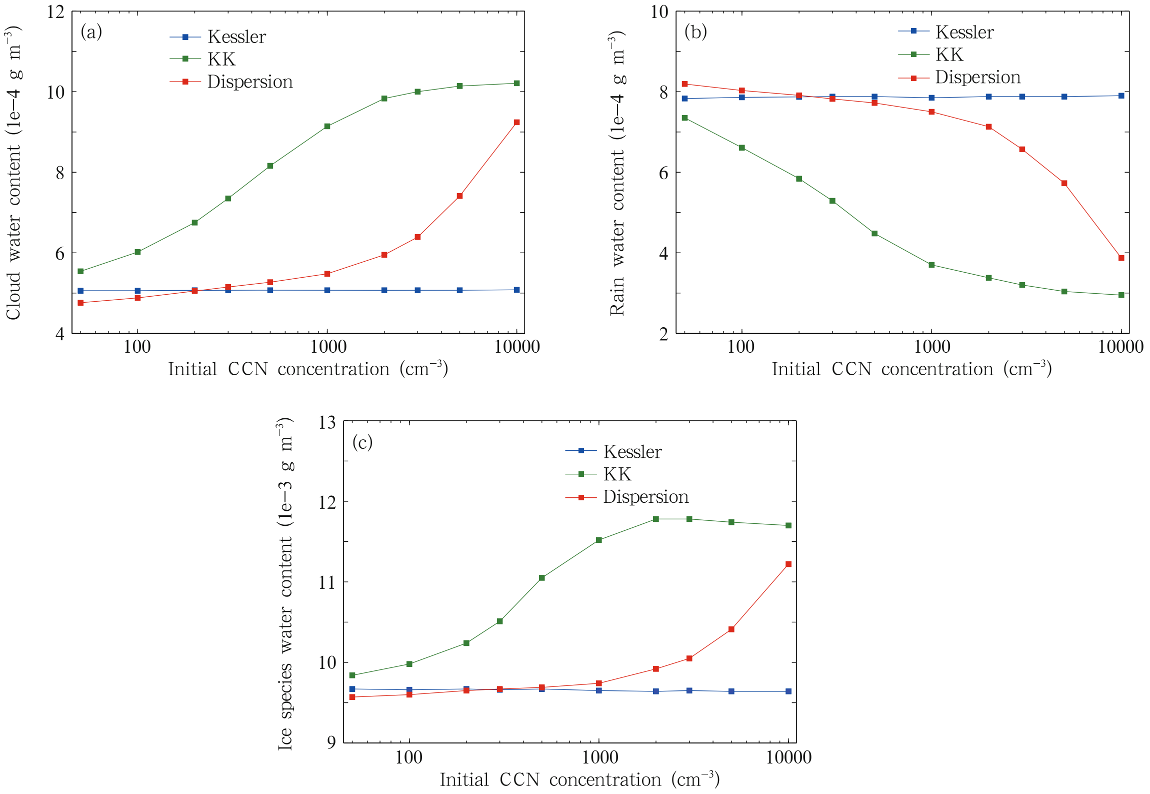

Fig. 3. Domain average water content of hydrometeors within 3 h of integration under various initial CCN concentrations for the three autoconversion parameterization schemes. (a) Cloud, (b) rain, and (c) ice species including ice, snow, and graupel.

content is higher for the Dispersion scheme than that for the KK scheme. These are because the increase in the cloud droplet spectral dispersion enhanced the autoconversion process and converted more cloud water into rain water in the Dispersion scheme. For the Dispersion scheme, the water content of ice species is significantly lower than that of the KK scheme, because fewer cloud droplets in the former can be transported and frozen into cold cloud regimes to form ice hydrometeor species.

3.3 Aerosol effects on accumulated surface precipitation

In this subsection, we show that aerosol-induced precipitation change is strongly dependent on the autoconversion parameterization scheme. Figure 4 shows the total surface precipitation with respect to the initial CCN number concentration for the three autoconversion schemes. Figure 4a shows a weak increase in surface precipitation (from 0.0786 to 0.0804 mm) in response to the increasing CCN number concentration for the Kessler scheme. For the KK scheme (Fig. 4b), the surface accumulated precipitation decreased markedly from 0.0809 to 0.0265 mm with the increasing CCN number concentration, and for the Dispersion scheme (Fig. 4c), the change in precipitation induced by aerosols was non-monotonic. The surface precipitation increased with the CCN number concentration from 50 to 2000 cm^{-3}, the maximum value can reach 0.0826 mm for the CCN number concentration at 2000 cm^{-3} (threshold value). The precipitation amount decreased when the CCN number concentration exceeded this threshold value.

Figures 5a and 5b indicate that aerosol-induced precipitation change is mainly determined by the corresponding rain water content. For the Kessler scheme, the autoconversion rate was enhanced with the cloud water content and it did not vary with the cloud droplet number concentration. Therefore, the slightly increased rain water content induced by more

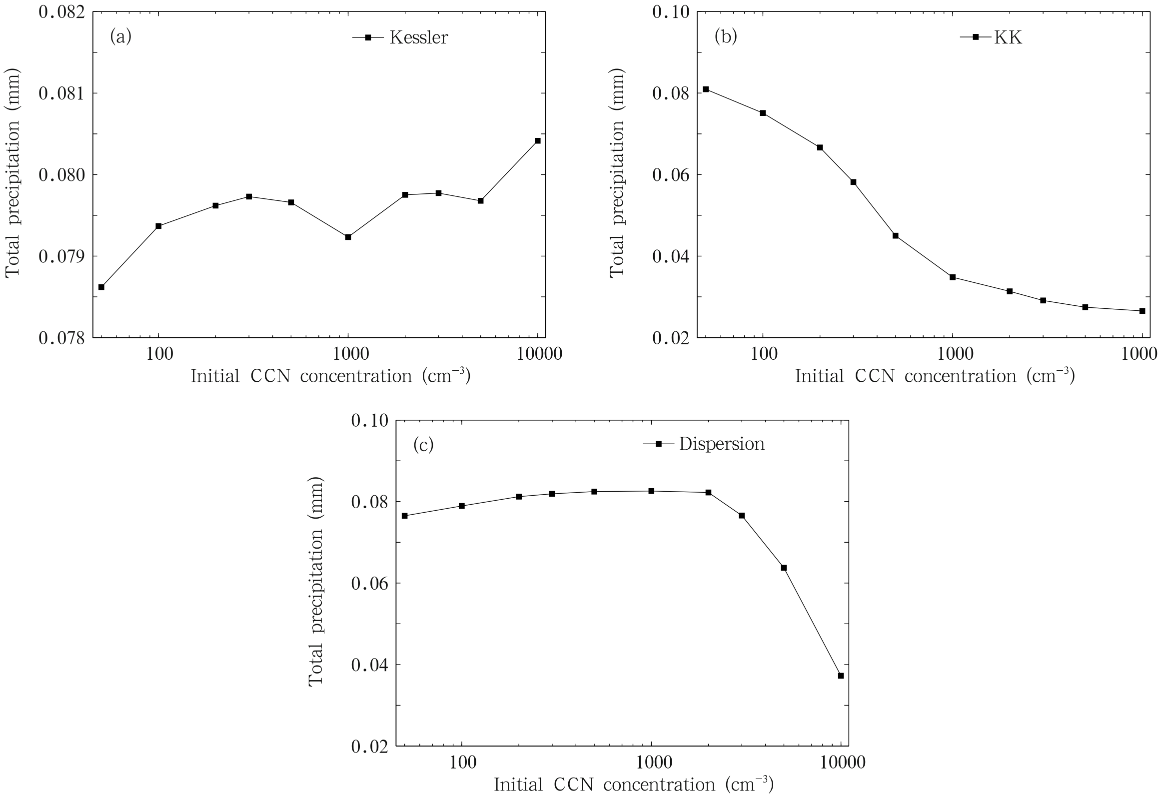

Fig. 4. Responses of the total accumulated surface precipitation to the changes in initial CCN number concentration for the three autoconversion parameterization schemes. (a) Kessler scheme, (b) KK scheme, and (c) Dispersion scheme.

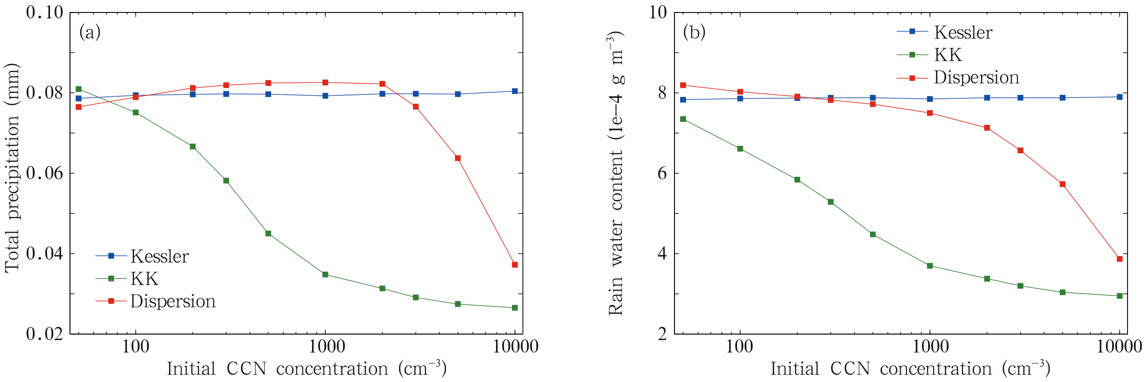

Fig. 5. Responses of (a) the total accumulated surface precipitation and (b) domain average rain water content within 3 h of integration to changes in the initial CCN number concentration for the three autoconversion schemes.

activated cloud water can lead to a weak increase in surface precipitation. Because the KK scheme considers the aerosol indirect effect, more and smaller cloud droplets induced by aerosols made the autoconversion process less efficient, which resulted in lower rain water content and reduced precipitation. The Dispersion scheme represents the indirect effects of aerosols and the influence of spectral dispersion. The autoconversion process can be enhanced by increasing spectral dispersion, which compensates for part of the decreasing autoconversion efficiency induced by aerosols. The enhanced precipitation with increasing aerosols at lower CCN conditions may be explained by the combined effects of the higher rain water content and additional mixed phase processes. Moreover, the decreased precipitation at high CCN conditions is likely because of the extremely suppressed conversion from cloud droplets to rain drops.

Note that, precipitation varies non-monotonically with the Dispersion scheme, increasing with aerosols at lower concentrations and decreasing at higher concentrations. These results are in good agreement with the findings about the impacts of aerosols on precipitation in Li et al. (2008) and Lim and Hong (2010). Hence, the results obtained in this study based on the Dispersion scheme are likely more reliable than those derived from the Kessler and KK schemes.

4. Summary

In this paper, we used the Kessler, KK, and Dispersion autoconversion parameterization schemes to investigate the aerosol indirect effects on cloud microphysical properties and surface precipitation for a deep convective cloud system under aerosol concentrations from 50 to 10000 cm^{-3}. Our results show that aerosol-induced precipitation change is strongly dependent on the autoconversion parameterization schemes. For the Kessler scheme, the average cumulative precipitation was enhanced slightly with the increase in aerosol concentrations. For the KK scheme, surface precipitation was reduced significantly with increasing aerosols. For the Dispersion scheme, the total precipitation varied non-monotonically, increasing with aerosols at lower concentrations and decreasing at higher concentrations. These different trends in aerosol-induced precipitation change were mainly due to changes in rain water content under the various autoconversion parameterization schemes. Therefore, our results suggest that an accurate representation of the cloud-to-rain autoconversion process is needed for advancing the scientific understanding of aerosol-cloud-precipitation interactions (Boucher et al., 1995; Rotstayn and Liu, 2005).

Note that several environmental parameters such as atmospheric relative humidity, vertical wind shear, and CAPE may influence the aerosol-induced effects on cloud microphysical properties and surface precipitation (Tao et al., 2012). However, the present study is not focused on different environmental parameters associated with aerosol-cloud-precipitation interactions. Variations in relative humidity, vertical wind shear, and CAPE may result in the distinct aerosol effects on precipitation for different autoconversion parameterization schemes.

Additionally, the Dispersion scheme displayed a non-monotonic change in surface precipitation with increasing aerosols, which is in good agreement with recent findings about aerosol-induced changes in precipitation (Li et al., 2008; Lim and Hong, 2010). Therefore, we believe that the Dispersion scheme considering spectral dispersion is more reliable for improving the understanding of the aerosol indirect effects.

REFERENCES

Albrecht, B. A., 1989: Aerosols, cloud microphysics and fractional cloudiness. *Science*, **245**, 1227–1230.

Beheng, K. D., 1994: A parameterization of warm cloud microphysical conversion processes. *Atmos. Res.*, **33**, 193–206.

Berry, E. X., and R. L. Reinhardt, 1974: An analysis of cloud drop growth by collection. Part II: Single initial distributions. *J. Atmos. Sci.*, **31**, 1825–1831.

Boucher, O., H. LeTreut, and M. B. Baker, 1995: Precipitation and radiation modelling in a GCM: Introduction of cloud microphysical processes. *J. Geophys. Res.*, **100**, 16395–16414.

Cheng, C.-T., W.-C. Wang, and J.-P. Chen, 2007: A modeling study of aerosol impacts on cloud microphysics and radiative properties. *Quart. J. Roy. Meteor. Soc.*, **133**, 283–297, doi: 10.1002/qj.25.

Han, J.-Y., J.-J. Baik, and H. Lee, 2014: Urban impacts on precipitation. *Asia-Pac. J. Atmos. Sci.*, **50**, 17–30, doi: 10.1007/s12143-014-0016-7.

Kaufman, Y. J., and T. Nakajima, 1993: Effect of Amazon smoke on cloud microphysics and albedo-analysis from satellite imagery. *J. Appl. Meteor.*, **32**, 729–744, doi: 10.1175/1520-0450(1993)032<0729:EOASOC>2.0.CO;2.

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulation. *Meteor. Monogr.*, No. 32, Amer. Meteor. Soc., 84 pp.

Khain, A., D. Rosenfeld, and A. Pokrovsky, 2005: Aerosol impact on the dynamics and microphysics of deep convective clouds. *Quart. J. Roy. Meteor. Soc.*, **131**, 2639–2663.

Khairoutdinov, M., and Y. Kogan, 2000: A new cloud physics parameterization in a large-eddy simulation model of marine stratocumulus. *Mon. Wea. Rev.*, **128**, 229–243.

Lebo, Z. J., and J. H. Seinfeld, 2011: Theoretical basis for convective invigoration due to increased aerosol concentration. *Atmos. Chem. Phys.*, **11**, 5407–5429, doi: 10.5194/acp-11-5407-2011.

Levin, Z., and W. R. Cotton, 2009: *Aerosol Pollution Impact on Precipitation: A Scientific Review.* Springer Press, 386 pp.

Li, G. H., Y. Wang, and R. Y. Zhang, 2008: Implementation of a two-moment bulk microphysics scheme to the WRF model to investigate aerosol-cloud interaction. *J. Geophys. Res.*, **113**, D15211, doi: 10.1029/2007JD009361.

Lim, K.-S., and S.-Y. Hong, 2010: Development of an effective double-moment cloud microphysics scheme with prognostic cloud condensation nuclei (CCN) for weather and climate models. *Mon. Wea. Rev.*, **138**, 1587–1612, doi: 10.1175/2009MWR2968.1.

Liu, Y., and P. H. Daum, 2004: Parameterization of the autoconversion process. Part I: Analytical formulation of the Kessler-type parameterizations. *J. Atmos. Sci.*, **61**, 1539–1548.

Liu, Y. G., P. H. Daum, and R. L. McGraw, 2005: Size truncation effect, threshold behavior, and a new type of autoconversion parameterization. *Geophys. Res. Lett.*, **32**, L11811, doi: 10.1029/2005GL022636.

Lohmann, U., P. Stier, C. Hoose, et al., 2007: Cloud microphysics and aerosol indirect effects in the global climate model ECHAM5-HAM. *Atmos. Chem. Phys.*, **7**, 3425–3446.

Martin, G. M., D. W. Johnson, and A. Spice, 1994: The measurement and parameterization of effective radius of droplets in warm stratocumulus clouds. *J. Atmos. Sci.*, **51**, 1823–1842.

Morrison, H., 2012: On the robustness of aerosol effects on an idealized supercell storm simulated with a cloud system-resolving model. *Atmos. Chem. Phys.*, **12**, 7689–7705, doi: 10.5194/acp-12-7689-2012.

Morrison, H., J. A. Curry, and V. I. Khvorostyanov, 2005: A new double-moment microphysics parameterization for application in cloud and climate models. Part I: Description. *J. Atmos. Sci.*, **62**, 1665–1677.

Morrison, H., and A. Gettelman, 2008: A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, version 3 (CAM3). Part I: Description and numerical tests. *J. Climate*, **21**, 3642–3659.

Pruppacher, H. R., and J. D. Klett, 1997: *Microphysics of Clouds and Precipitation.* Kluwer Academic, 954 pp.

Ramanathan, V., P. J. Crutzen, J. T. Kiehl, et al., 2001: Aerosols, climate, and the hydrological cycle. *Science*, **294**, 2119–2124, doi: 10.1126/science.1064034.

Rotstayn, L. D., and Y. G. Liu, 2005: A smaller global estimate of the second indirect aerosol effect. *Geophys. Res. Lett.*, **32**, L05708, doi: 10.1029/2004GL021922.

Skamarock, W. C., J. B. Klemp, J. Dudhia, et al., 2005: A description of the Advanced Research WRF Version 2, NCAR Tech. Note NCAR-TN-468+STR, Natl. Cent. for Atmos. Res., Boulder, CO, 113 pp.

Sundqvist, H., E. Berge, and J. E. Kristjansson, 1989: Condensation and cloud parameterization studies with a mesoscale numerical weather prediction model. *Mon. Wea. Rev.*, **117**, 1641–1657.

Tao, W.-K., J.-P. Chen, Z. Q. Li, et al., 2012: Impact of aerosols on convective clouds and precipitation. *Rev. Geophys.*, **50**, RG2001, doi: 10.1029/2011RG000369.

Van den Heever, S. C., G. G. Carrió, E. R. Cotton, et al., 2006: Impacts of nucleating aerosol on Florida storms. Part I: Mesoscale simulations. *J. Atmos. Sci.*, **63**, 1752–1775.

Wang, C., 2005: A modeling study of the response of tropical deep convection to the increase of cloud condensation nuclei concentration: 1. Dynamics and microphysics. *J. Geophys. Res.*, **110**, D21211, doi: 10.1029/2004JD005720.

Xie, X. N., and X. D. Liu, 2009: Analytical three-moment autoconversion parameterization based on generalized gamma distribution. *J. Geophys. Res.*, **114**, D17201, doi: 10.1029/2008JD011633.

Xie, X. N., and X. D. Liu, 2011: Effects of spectral dispersion on clouds and precipitation in mesoscale convective systems. *J. Geophys. Res.*, **116**, D06202, doi: 10.1029/2010JD014598.

Xie, X. N., and X. D. Liu, 2013: Analytical studies of the cloud droplet spectral dispersion influence on the first indirect aerosol effect. *Adv. Atmos. Sci.*, **30**, 1313–1319, doi: 10.1007/s00376-012-2141-5.

Xie, X. N., X. D. Liu, Y. R. Peng, et al., 2013: Numerical simulation of clouds and precipitation depending on different relationships between aerosol and cloud droplet spectral dispersion. *Tellus B*, **65**, 19054, doi: 10.3402/tellusb.v65i0.19054.

Zhang Xiaoye, 2007: Aerosol over China and their climate effect. *Adv. Earth Sci.*, **22**, 12–16. (in Chinese)