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Key Points:
- The predicted particle properties (P3) microphysics scheme is formally implemented in a vector vorticity equation cloud-resolving model (VVM).
- The P3 scheme exhibits stronger extreme precipitation under a strongly forced environment compared to the original scheme.
- The reduced melting effects associated with strong convective updrafts in P3 can result in more extreme precipitation.

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Abstract
This study investigates the effects of microphysical processes on the precipitation spectrum in a strongly forced environment using the vector vorticity cloud-resolving model (VVM). Experiments are performed under imposed advective cooling and moistening with two microphysics parameterizations: the predicted particle properties scheme (P3) and Lin scheme (VVM-Lin). Even though the domain-averaged precipitation is similar in the two experiments, P3 exhibits stronger extreme precipitation in the spectrum compared with VVM-Lin. Changes in convective structures are responsible for such a difference. Using the isentropic analyses, we identify that in P3, stronger convective updrafts take place in the high $\theta_v$ regime, where air parcels rarely reach. This is caused by the reduced melting of rimed ice particles for energetic parcels. Through defining convective core clouds, the relation between the convective structure on the isentropic diagram and the extreme precipitation can be identified. The shifts toward extreme intensity in the precipitation spectrum suggest that the microphysical processes have significant impacts on the extreme precipitation by the convective core clouds. The treatment of microphysics has significant impacts on the convective structures and then alter the probability of extreme events under the strongly forced environment.

Plain Language Summary
The microphysical parameterization typically represents cloud microphysical processes in the numerical models. In this study, the authors implemented a new parameterization (P3) in the model. The results show that extreme precipitation is more likely to occur when the environment is warm and moist compared with the original microphysics scheme. The change of the extreme precipitation is associated with the reduced melting effect in an ascending parcel. The melting of ice particles weakens the upward velocity of the parcel and then reduce the extreme precipitation. P3 can reduce the melting effect by its ability to represent fast-falling hail particles, which can leave the parcel rapidly.

1. Introduction
Cloud microphysics parameterizations play an essential role in the cloud-resolving simulations of convective systems. Various simplifications are made in the representation of microphysical processes in the cloud-resolving models producing uncertainties of the simulated cloud structures and precipitation. Many studies have investigated these uncertainties through case-oriented (Adams-Selin et al., 2013; Morrison & Milbrandt, 2011; Tao et al., 2011, 2016) or cumulus ensembles simulations (Grabowski et al., 1999; Johnson et al., 2007; Khairoutdinov & Randall, 2003). The former one access the overall performance of microphysics parameterizations for a specific real case or an idealized event. Tao et al. (2011) tested the performance of the Goddard microphysics parameterizations in simulating hurricane Katrina in the WRF model. The simulated hurricane is strongest in their study when they turned off the ice processes. Morrison and Milbrandt (2011) have illustrated that the choice of graupel as rimed ice led to a weaker cold pool and less precipitation compared to hail for an idealized supercell case. Adams-Selin et al. (2013) showed that the structure and the strength of an idealized convective system are sensitive to the predefined properties of graupel. Tao et al. (2016) improved the Goddard 4ICE scheme by revising formulations of ice processes, and the modified scheme showed better performances for continental squall cases. These studies suggest that ice processes are essential to the convective structures. The other approach is used initially to study convective variabilities in an idealized simulation with imposed large-scale destabilization and moisture source (Yanai et al., 1973). Grabowski et al. (1999) pointed out that cloud microphysics can considerably affect mean temperature and moisture profiles, and its impacts should be evaluated in cumulus ensemble...
simulations. Khairoutdinov and Randall (2003) showed that the mean hydrometer profiles are sensitive to prescribed parameters. For instance, the increase of ice aggregation threshold leads to more cloud ice in the upper atmosphere, and the increase of ice aggregation rates resulted in less cloud water and cloud ice. Johnson et al. (2007) found that convective precipitation became stronger within a narrow region when the ice microphysics is eliminated. The above studies demonstrate the importance of adequately formulating ice-processes in the cloud-resolving simulations of convective systems. In this study, we adopt the cumulus ensemble approach.

The predicted particle properties scheme (P3, Morrison & Milbrandt, 2015; Milbrandt & Morrison, 2016) has been implemented in the vector vorticity equation cloud-resolving model (VVM, Jung & Arakawa, 2008; Chien & Wu, 2016; Wu et al., 2019) to better represent the ice processes. In this study, we investigate the differences between the P3 scheme and the existing three-phase cloud microphysics parameterization (Krueger et al., 1995; Lin et al., 1983). We perform the idealized simulations with the large-scale forcing to obtain large samples of strong convective systems and their overall statistics. Instead of particular events from the case-oriented simulations. In addition, we also use the isentropic analysis method (Pauluis & Mrowiec, 2013) to diagnose differences in convective structures. This method has been applied to high-resolution model studies: moist convection (Pauluis, 2016; Pauluis & Mrowiec, 2013), hurricane simulation (Mrowiec et al., 2016), and multiscale atmospheric overturning (Chen et al., 2018). They took advantage of the ability of this technique to capturing the irreversible convective overturning, and its ability is suitable for us to investigate convective responses of P3 and Lin. The experiment setup and analysis method are described in section 2. Section 3 presents the results of the comparison, and a summary and discussion are presented in section 4.

2. Materials and Methods

2.1. The Model Description

The vector vorticity equation cloud-resolving model (VVM) was developed by Jung and Arakawa (2008). The distinctive dynamical core is the adoption of the three-dimensional anelastic vorticity equations instead of the momentum equations. The velocity vectors are diagnosed through a three-dimensional elliptic equation and the vertical integrals of the vorticity. The use of the horizontal vorticities as prognostic variables removes the pressure gradient force in the governing equation. In this approach, the dynamics can respond to the thermal forcing directly. Therefore, the model can better represent the local-scale circulations due to a strong buoyancy gradient, such as land-sea breeze and cold pool fronts. The orographic effect is represented by implementing the immersed boundary method on the vorticity equation (Chien & Wu, 2016; Wu & Arakawa, 2011). The VVM is coupled with the Noah land surface model and the rapid radiative transfer model to more realistically simulate the interactions between convection, radiation, and land surface (Wu et al., 2019). This model has been used to study the unified parameterization for deep convection (Arakawa & Wu, 2013; Wu & Arakawa, 2014), stratocumulus transition (Tsai & Wu, 2016), aggregated convection (Chen & Wu, 2019; Tsai & Wu, 2017), afternoon thunderstorms over complex topography (Kuo & Wu, 2019; Wu et al., 2019), and the quasi-three-dimensional multiscale modeling framework (Jung et al., 2019; Jung & Arakawa, 2016).

2.2. The Experiment Setup

Two experiments performed in this study share the same model setup except for the treatment of microphysics. Due to strong coupling with the dynamics, the direct impact of microphysical processes is difficult to evaluate (Grabowski, 2014). Therefore, we impose strong and constant-in-time large-scale forcing in the cyclic domain to reach the quasi-equilibrium state (Arakawa & Schubert, 1974). In this case, the domain-averaged precipitation is strongly constrained by the large-scale forcing, and the direct impact of microphysical processes on the precipitation spectrum can be evaluated. Besides, the land surface and radiative processes are not applied to get rid of complicated interactions among these processes. The prescribed vertical profile of the forcing follows Arakawa and Wu (2013), which is chosen to counteract the apparent heat source and moisture sink typical of the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) phase III after some idealization. The constant cooling rate of 2 K day$^{-1}$ is also included to mimic radiative cooling. The simulations are initialized with the mean thermodynamic profiles from the GARP GATE phase III, and the background wind fields are nudged to calm state with a 2-hr time
scale. The modeled domain is $512 \times 512$ km$^2$ with a 2 km horizontal grid spacing and a vertical grid spacing that stretches from 100 m at the bottom to roughly 1 km at the model top (20 km).

2.3. Microphysics Schemes

The ice microphysics parameterizations used in this study are briefly introduced below. The original scheme (VVM-Lin) used in the VVM is a single-moment parameterization developed by Lin et al. (1983), and some ice processes have been corrected by Krueger et al. (1995). The scheme separates ice-phase hydrometers into three predefined categories: cloud ice, snow, and graupel. The division of ice particles leads to the use of artificial parameters, such as the threshold or conversion rate between each category. Characteristics of the categories are prescribed, which causes discontinuous transition between ice species. On the other hand, the predicted particle properties scheme (P3) represents ice particles based on particle properties (Milbrandt & Morrison, 2016; Morrison et al., 2015; Morrison & Milbrandt, 2015). Four bulk ice properties, total mass, total number, rimed mass, and rimed volume, are used to represent the ice particles with four degrees of freedom. The approach evolves the ice properties continuously and avoids the use of artificial parameters. The P3 scheme has been tested by Morrison and Milbrandt (2015) and Morrison et al. (2015), and it can produce consistent results compared with other sophisticated two-moment microphysics schemes, and it is more computationally efficient. These two microphysics parameterizations are used in two simulations, respectively.

2.4. The Isentropic Analysis

The isentropic analysis method proposed by Pauluis and Mrowiec (2013) is used to diagnose differences in convection due to the microphysics in this study. The isentropic distribution is calculated through conditionally sampling according to the air parcel's equivalent potential temperature. The frozen equivalent potential temperature (Pauluis, 2016), $\theta_{ei}$, is used to include the latent heat of freezing, and its definition is

$$
(C_{pd} + C_{rT}) \ln \frac{\theta_{ei}}{T_f} = \left[ C_{pd} + r_l C_l + (r_v + r_i) C_i \right] \ln \frac{T}{T_f} - R_d \ln \frac{P_d}{P_0} + (r_v + r_i) \frac{L_f}{T_f} + r_v \frac{L_v}{T} - r_i R_i \ln \mathcal{H}.
$$

(1)

In Equation 1, $C_{pd}$, $C_l$, and $C_i$ are the specific heat capacities at a constant pressure of dry air, liquid water, and ice, respectively; $r_l$, $r_v$, $r_i$, and $r_i$ are the mixing ratio of total water, water vapor, liquid water, and ice, respectively; $L_v$ and $L_f$ are the latent heats of vaporization and freezing, respectively; $R_d$ and $R_i$ are the specific gas constant of dry air and water vapor, respectively; $\mathcal{H}$ is the relative humidity with reference to liquid water; $P_0$ is the reference pressure, $10^5$ Pa; $T_f$ is the freezing temperature of the water, 273.15 K; and $T$ is the temperature of the air. The isentropic distribution of a given variable $f$ is defined as

$$
\langle f \rangle(x, y, \theta_{ei}) = \frac{1}{PL_x L_y} \int_0^PL_x L_y \int_0^T f(x, y, z, t) \delta(\theta_{ei} - \theta_{ei}(x, y, z, t)) dz dt.
$$

(2)

Here, $P$ is the sampling period, and $L_x$, $L_y$ are horizontal sampling lengths. $\delta$ is an approximate form of Dirac delta function,

$$
\delta(\theta_{ei} - \theta_{ei}(x, y, z, t)) = \begin{cases} 1/\Delta \theta_{ei}, & \theta_{ei} - 0.5 \Delta \theta_{ei} \leq \theta_{ei} < \theta_{ei} + 0.5 \Delta \theta_{ei} \\ 0, & \text{elsewhere} \end{cases}
$$

(3)

where $\theta_{ei}$ is the frozen equivalent potential temperature, and $\theta_{ei}$ is the sampling reference, and $\Delta \theta_{ei}$ is the width of the finite bin. The mass-weighted isentropic mean of the variable,

$$
\tilde{f}(x, y, \theta_{ei}) = \frac{\langle \rho f \rangle(x, y, \theta_{ei})}{\langle \rho \rangle(x, y, \theta_{ei})}
$$

(4)

is defined to approximate parcel's thermodynamic and dynamic properties on the isentropic coordinate. Reversible gravity oscillations are canceled out through this conditional sampling technique, and the irreversible convective overturning can be retained in the isentropic distribution. Warm, moist ascending air parcels are also separated from environmental subsidence. This method can provide the paths that a parcel would potentially undergo, and the parcel's properties can be estimated by isentropic mean technique. The
isentropic analysis method allows us to compare our results based on thermodynamics and the parcel theory rather than complex flow structures.

3. Results

3.1. Vertical Structure

The vertical cross-section of the simulated convective systems demonstrates differences in convective structures between the VVM-Lin and P3. The convective systems consist of the convective and stratiform regions visualized by the shading of the total ice mixing ratio (Figures 1a and 1b). In the P3, the distribution of ice particles is diagnosed through four bulk ice properties. We can visualize the ice species through the mass-weighted mean particle density (Figures 1c and 1d). At the top of the anvil cloud, the density is close to 917 km m$^{-3}$, which represents the less-rimmed small ice particle. The density of the stratiform cloud is around 400 km m$^{-3}$, which represents the medium-rimmed particle or the large aggregate. The higher density in the convective region suggests that there are heavy-rimed or hail particles due to the convective updraft. In the VVM-Lin, the total ice mixing ratio is the sum of all ice species: cloud ice, snow, and graupel. The cloud ice mainly exists above 12 km, and the graupel is the dominant specie below 8 km (Figure 1a). The mass-weighted density (Figure 1c) is the linear combination of predefined densities (cloud ice: 917 km m$^{-3}$, snow: 100 km m$^{-3}$, graupel: 400 km m$^{-3}$). The predefined densities change dramatically from category to category, and this approach causes a sharp change in the vertical structure. For example, the density increases five times from the snow-dominant region to the cloud-ice-dominant region at the edge of the stratiform cloud (Figure 1c). Below 8 km, the density is nearly constant in the graupel-dominant region. This result suggests that the VVM-Lin cannot represent the variability of rimed ice particles in different regions in the convective systems. On the other hand, the P3 exhibits great variabilities between the convective and stratiform regions with continuous density distribution. The results show that the distribution and variability of the ice-phase particles are better represented by the P3 scheme compared to the VVM-Lin.

3.2. Convective Statistics

It is well-known that the interactions between the large-scale forcing and the response from convective development remain quasi-equilibrium, especially when the forcing is strong (Arakawa, 2004). The concept can be visualized by the time evolution of domain-averaged precipitation in Figure 2a. The domain-averaged precipitation is similar in both simulations with roughly 60 mm day$^{-1}$ after the initial spin ups suggesting that the convective systems are actively responding to the large-scale forcing. Thus, the impact of the VVM-Lin and the P3 on the precipitation distribution can be fairly compared with each other. We analyze the results in the last 12 hr in the rest of the manuscript. Even though the domain-averaged precipitation is close to each other, the precipitation could be contributed by strong convective updrafts within a narrow area or moderate updrafts in a broad area. The different characteristics of convective systems can be examined by the precipitation spectrum. The precipitation area is defined as a grid box where the ten-minute surface precipitation rate is larger than 0.5 mm hr$^{-1}$ (Figure 2b). The spectrum shows that the probability of precipitation logarithmically decreases with the increase of the precipitation rate. The P3 exhibits a higher probability than the VVM-Lin when the precipitating rate is over 40 mm hr$^{-1}$. The differences become larger as the precipitation rate gets more extreme. The results show that the different treatment of ice microphysics processes can result in the change of precipitation spectrum under the constraint of quasi-equilibrium.

The difference in precipitation spectrum would be associated with the change of convective structures. The cause of such a difference is further analyzed through the isentropic distributions (Figure 3). The probability density function for the VVM-Lin (Figure 3a) and the P3 (Figure 3b) is largest near the domain-averaged $\varepsilon_{ei}$ profiles, and the distribution drops slowly toward high $\varepsilon_{ei}$. This distribution implies that most of area is covered by cold and dry subsidence, and moist convection occurs in narrow regions. The vertically tilt distributions to the mean $\varepsilon_{ei}$ are collocated with the positive vertical velocity in the high $\varepsilon_{ei}$ region (Figures 3c and 3d). This tilting distributions of the isentropic-convective streamfunction could be used to approximate the path of ascending air parcels, so we simply call this region as isentropic-convective (IC) region. Air parcels in the P3 have stronger upward isentropic-mean vertical velocity in the IC region than those in the VVM-Lin, especially in the upper layer. In the VVM-Lin, the velocity distribution is divided into two updraft regions in the lower and upper layer, while it continuously extends from lower level to upper level in the P3. The ascending air parcels in the VVM-Lin slow down the vertical velocity after entering the freezing level.
Figure 1. The x-z cross-section of convection systems in VVM-Lin (a, c) and P3 (b, d) at $t = 12$ hr. Upper panels present the mixing ratio of solid particles (gray shading, g kg$^{-1}$) and rainy region (cyan shading and blue line). The color contours in (a) indicate the dominant ice specie which the mass faction of the specie is larger than 0.5. The mass-weighted mean particle density (kg m$^{-3}$) of solid particles is showed in bottom panels.

Figure 2. (a) The time evolution of domain-averaged precipitation (mm hr$^{-1}$). (b) The occurrence of precipitation is sampled with 2 mm hr$^{-1}$ intervals on the intensity spectrum when the precipitation greater than 0.5 mm hr$^{-1}$. 

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but the parcels do not decelerate in the P3. This difference in velocity distribution can be attributed to the variability of the rimed ice, and the cyan contours in Figures 3c and 3d represent the heating rate due to melting processes. The VVM-Lin exhibits stronger cooling around the freezing level in the IC region.

Figure 3. The last 12 hr isentropic distributions of the VVM-Lin (a, c) and P3 (b, d). The probability density function of air parcels' frozen equivalent potential temperature ($\theta_{ei}$) is presented by the color shading in upper panels. The isentropic convective stream function (kg m $^{-2}$ s $^{-1}$) is presented as the dashed contours from -0.01 kg m $^{-2}$ s $^{-1}$ (outside) to -0.07 kg m $^{-2}$ s $^{-1}$ (inside) interval. The isentropic-mean vertical velocity is shown as the color shading in bottom panels, and the cyan contours present the cooling rate of melting with 0.5 K hr $^{-1}$. The black lines are the mean $\theta_{ei}$ profiles within the sampling period.

Figure 4. (a) and (b), respectively, show the mixing ratio of all ice species in the VVM-Lin and the P3 in gray shading. The red contours represent the ice part of the convective core cloud. See text for more details. The length of cyan arrows indicates the bulk terminal velocity of precipitating ice particles, which is greater than 1 m s $^{-1}$.
predefined graupel particles lead to strong cooling effect because of slow falling speed in the VVM-Lin. On the other hand, P3 can represent hail-like and faster-falling particles, so the cooling is weaker than that in the P3. The cold air entrains into warm parcels and then reducing the buoyancy and updraft. The stronger cooling effect causes the gap of vertical velocity in the VVM-Lin. The inhibition of updraft does not take place, so there is stronger convective updraft in the P3. In addition, we examine the heating due to the ice deposition processes on the isentropic diagram, but its effect is not significant around the freezing level (figure not shown). The impact of ice variability on the convective structures is identified through the isentropic analysis, and the change in the convective structures would alter the probability of the extreme precipitation.

3.3. Convective Core Cloud Analyses

We identify the convective core cloud following Tsai and Wu (2017) to link the changes in convective structures and extreme precipitation. A cloudy grid is defined by the summation of all ice-phase species and cloud water greater than $10^{-5}$ kg kg$^{-1}$ in this study, and contiguous cloudy grids are connected as a cloud object. The convective core cloud is selected by imposing additional criteria: The cloud base is lower than 2 km, the cloud top is higher than 6 km, and the vertical velocity is greater than 0.5 m s$^{-1}$. We demonstrate that the convective core cloud in the simulations in Figure 4 based on the cross-sections in Figure 1. In the VVM-Lin, the ice particles have similar bulk terminal velocity around the freezing level in the convective core cloud and the stratiform region (Figure 4a). On the other hand, the P3 scheme can represent different characteristics of the ice particles: fast-falling particles in the convective region and slow-falling ones in the stratiform region. This result is consistent with the isentropic analysis, and the change in the extreme precipitation could be attributed to the differences in the convective region. The contribution of convective core clouds to the precipitation is defined as the fraction of precipitation grids covered by the projection to all precipitation grids. Figure 5a shows that more than 80% of the precipitation greater than 40 mm hr$^{-1}$ is contributed by the convective core clouds. The occurrence of the convective core clouds on the isentropic diagram is presented in Figure 5b. The distribution of the fraction corresponds to the change due to microphysics processes in the IC region (Figure 5b), so the differences in precipitation spectrum can be attributed to the changes of convective structures. We further analyze the spectrum of mean and maximum precipitation based on the convective system. The system-based analysis shows that the convective core cloud tends to produce more precipitation in the P3 (Figure 5c). The P3 has a shift of the distribution toward more extreme intensity in Figure 5d. The ability to represent the different rimed ice between convective and stratiform region enhances the extreme precipitation through the change in the convective structures.

4. Conclusions

In this study, we implement the predicted particle properties (P3) scheme and examine its impact on the precipitation spectrum compared to the original VVM-Lin scheme. Two idealized simulations are performed by using the vector vorticity equation cloud-resolving model (VVM). Strong large-scale forcing is imposed in the cyclic domain to constrain the domain-averaged precipitation to obtain large samples.
of strong convective systems. The P3 exhibits a higher variation of the ice particles with a single category; for example, heavy-rimed particles in the convective updraft and large aggregates in the stratiform region. In the VVM-Lin, the use of graupel as the rimed ice species results in the monotonous feature of the ice particles in a different region. The impacts of the different representations of the rimed ice particles on the convective structures are investigated by the isentropic analyses. The melting of the rimed particles results in the cooling in the convective updraft. The cooling effect is stronger in the convective region in the VVM-Lin due to slower falling speed of the graupel and, therefore, the weakening of the convective updraft. On the other hand, the P3 can produce fast-falling hail-like particles in the convective region, so the convective updraft is not inhibited by the cooling effect. The change of convective structures is identified as the main reason for the shift in the precipitation spectrum through the convective core cloud analyses. The more realistic representation of the ice particles reduces the cooling effect and results in more extreme precipitation in the P3.

This study demonstrates the role of convective structure change in connecting microphysical processes and extreme precipitation. Detailed microphysical effects modify the statistics of the convective structure leading to the change of the precipitation spectrum. In the future, the interactions among all other physical processes, such as radiation, turbulence, and boundary layer processes, can be evaluated using similar concepts. Depending on the process of interest, the specific experimental setup can be different. For example, the cloud-radiation interaction can be evaluated in the radiative-convective-equilibrium (RCE) simulations. The convective structure changes due to microphysical processes that can interact with the radiation leading to a different stage of convective aggregation. In this approach, we can compare the statistics of convective structure among various cloud-resolving simulations to understand the impacts of the specific physical processes.

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