1. INTRODUCTION

The representation of ice microphysics in models has a significant impact on quantitative precipitation forecasts, radiative transfer through clouds, and cloud-dynamical interactions (e.g., Rangno and Hobbs 1984; Lord et al. 1984). The one-moment bulk approach was first applied by Kessler (1969) to warm (ice-free) clouds based on the natural separation between cloud droplets and drizzle/rain. Thus, mixing ratio was separately predicted for each category (cloud droplets and drizzle/rain drops), with parameterized conversion rates (autoconversion and accretion) transferring the cloud water to drizzle/rain. The bulk approach was extended to the ice phase using a similar separation between cloud ice and large precipitating ice (e.g., Lin et al. 1983; Rutledge and Hobbs 1984). This separation was required since the empirical particle fallspeed-size relationships used in these schemes apply to only a limited size range (thus requiring separation of small and large ice particles). This approach also represents a legacy of the Kessler-type warm-rain scheme. However, the distinction between small and large particle modes is less clear for ice than liquid because large precipitating ice particles can be produced by both accretional and vapor depositional growth; rain is produced by accretional growth only. Precipitation ice is often further subdivided into different predefined categories (e.g., snow, aggregates, graupel, hail). The parameters needed for calculating microphysical process rates are specified a priori for each predefined ice category.

A key point is that in nature the boundaries between different ice categories (cloud ice, snow, graupel, hail) are difficult to define and transitions between various categories happen gradually. For instance, as ice crystals grow by diffusion of water vapor and aggregation, their mass and terminal velocities gradually increase, and they gradually move from the “cloud ice” into the “snow” category. The same is true for the growth by riming, where ice particles gradually increase their mass and rimed mass fraction, and move from the “snow” to the “graupel” category. In traditional schemes, there are no transitional regimes between various ice categories and conversion of ice from one category to another occurs in a single discrete step. For example, some schemes produce graupel immediately after a minimum riming rate or mixing ratio is reached. More detailed models prognose the particle density to more accurately determine the threshold for conversion to graupel (e.g., Ferrier 1994). However, none of these schemes treat the transitional regimes that represent the growth of a small ice particle into a large ice crystal or an aggregate (i.e., the snowflake), or growth of a rimed crystal into a graupel particle. This has the potential to produce undesirable thresholding behavior, i.e., model solutions may diverge depending whether a particular threshold (e.g., the cloud ice mixing ratio or the riming rate) is reached or not. Thus, significant sensitivity of the simulated clouds and precipitation to these thresholds has been noted (e.g., Rangno and Hobbs 1984; Thompson et al. 2004); these thresholds must therefore be tuned to produce desirable results.

In this paper, we propose a novel approach for parameterizing ice microphysics that shifts away from the traditional approach of predefined ice categories. Our approach allows the crystal habit and associated microphysical parameters to evolve during the simulation as a function of particle size and rimed mass fraction. The history of the rimed mass fraction is retained by predicting two ice mixing ratio variables: i) the mixing ratio due to vapor deposition and ii) the mixing ratio due to riming. It follows that the rimed mass fraction is derived locally from the ratio of the riming and total (riming plus deposition) mixing ratios. This approach allows the mass-dimension (m-D) and projected area-dimension (A-D) relationships to evolve according to the predicted rimed mass fraction and particle dimension. All relevant microphysical parameters in the scheme are based on these m-D and A-D relationships for self-consistency. This approach removes the need for arbitrary thresholds for conversions of small ice to snow during vapor deposition and/or aggregation, and conversion of crys-
tals to graupel during riming. The goal is to provide a physically-based treatment of the ice microphysics that accounts for the transitional regimes and avoids thresholding behavior while retaining a relatively simple and flexible framework.

2. DESCRIPTION OF THE NEW SCHEME

The two-moment bulk warm rain scheme of Morrison and Grabowski (2006; hereafter MG06) has been extended to the ice phase using the novel approach outlined in the Introduction. The new ice scheme is described in detail in Morrison and Grabowski (2008), and outlined here.

All ice microphysical processes and parameters are calculated consistently in terms of the particle mass-dimension (m-D) and projected area-dimension (A-D) relationships. These relationships are obtained across the whole range of particle sizes using observationally-based relations for different types of ice particles (available in the literature) and the rimed mass fraction predicted by the model. The history of rimed mass fraction is retained by predicting separately the mixing ratios of ice due to the vapor deposition, $q_{\text{dep}}$, and due to riming, $q_{\text{rim}}$. The change in ice mixing ratio due to water vapor deposition and initiation of ice by deposition/condensation freezing and freezing of cloud droplets contributes to $q_{\text{dep}}$. The change in ice mixing ratio due to collisions between ice particles and cloud droplets/rain (in subfreezing conditions) and ice initiation due to freezing of raindrop contributes to $q_{\text{rim}}$. Sublimation and melting (including melting due to rain-ice collisions above freezing) are applied to both $q_{\text{dep}}$ and $q_{\text{rim}}$. Since we also predict the ice number concentration $N$, there are a total of three prognostic variables for ice in the scheme.

Similarly to the liquid species (cloud droplets and rain) described in MG06a, the ice particle size distribution follows a generalized gamma distribution:

$$ N(D) = N_0 D^\mu e^{-\lambda D}, \quad (1) $$

where $D$ is the particle dimension (hereafter dimension refers to length of the major axis), $N_0$ is the “intercept” parameter, $\lambda$ is the slope parameter, and $\mu = 1/\eta^2 - 1$ is the spectral shape parameter ($\eta$ is the relative radius dispersion, the ratio between the standard deviation and the mean radius). These size distribution parameters are needed for calculation of the various microphysical process rates.

Parameters $N_0$ and $\lambda$ can be found by relating the PSD to the predicted number concentration $N$ and mixing ratio $q$ (note that for ice, $q = q_{\text{dep}} + q_{\text{rim}}$):

$$ N = \int_0^\infty N(D)dD, \quad (2) $$

where $m(D)$ is the particle mass and $N(D)$ is given by (1). A solution for the size distribution parameters $N_0$ and $\lambda$ in terms of $\mu$, $N$, and $q$ using (1) - (3) requires specification of the m-D relationship across the PSD. Note that although the A-D relationship is not used to derive the size distribution parameters using (1) - (3), it is needed, along with the size distribution parameters and m-D relationship, for calculation of several of the process rate (e.g., collection of cloud water and rain by ice particles).

For the ice phase, a complication arises because the m-D and A-D relationships vary as a function of crystal habit, degree of riming, and particle size. Thus, by predicting both $q_{\text{dep}}$ and $q_{\text{rim}}$ and retaining the history of bulk rimed mass fraction $F_r$ [defined as $F_r = q_{\text{rim}}/(q_{\text{rim}} + q_{\text{dep}})$], we seek to provide a physical basis for the evolution of m-D and A-D relations across a wide range of conditions. The m-D and A-D relationships as a function of crystal habit, rimed mass fraction, and particle size are detailed in Morrison and Grabowski (2008). The evolution of m-D and A-D as a function of rimed mass fraction follows from the conceptual model of Heymsfield (1982). Based on this model, rime accumulation in the crystal interstices increases the particle mass but not the particle dimension $D$, and such a picture is valid up to the point of a complete “filling-in” of crystal interstices. From this point the particle becomes a graupel and further riming increases both particle size and mass. Prior to the complete “filling-in” of the interstices, the rimed mass fraction of an individual crystal is assumed equal to the bulk rimed fraction $F_r$ and the particle dimension $D$ is determined by the crystal mass grown by diffusion of water vapor and aggregation.

3. DESCRIPTION OF THE KINEMATIC FRAMEWORK AND CASE STUDY

The bulk model with the new ice microphysics scheme was implemented in a 2D kinematic modeling framework similar to that presented by Szymowski et al. (1998). The kinematic framework employs a specified flow field, which allows for testing of the microphysics scheme in a framework that includes advective transport and particle sedimentation, while at the same time avoiding complications due to feedbacks between the dynamics and microphysics. In addition to the equations describing conservation of the mixing ratios and number concentrations of ice, cloud droplets, and rain, the kinematic model solves equations for the potential temperature and water vapor mixing ratio. These equations include advective transport and sinks/sources due to condensation/evaporation and latent heating. Transport in physical space is calculated using the 2D version of the MPDATA scheme.
(Smolarkiewicz and Margolin 1998). The vertical and horizontal grid spacing is 50 m over a domain that is 9 km wide and 3 km deep. The model time step is 0.5 sec.

Figure 1: Time evolution of horizontal maxima of cloud water mixing ratio, rain mixing ratio, ice/snow mixing ratio, and graupel mixing ratio at each vertical level using the traditional scheme.

The specified flow field varies in time, representing the evolution of an idealized shallow convective plume. The flow pattern consists of low-level convergence, upper-level divergence, and a narrow updraft at the center of the domain. Two flow configurations are tested, corresponding with a maximum updraft speed of 8 m s\(^{-1}\). The updraft speed is held constant at 1 m s\(^{-1}\) for the first 15 min, intensifies to a peak value of 8 m s\(^{-1}\) at 25 min, and decays to zero after 40 min. The simulated time period is from \(t = 0\) to 90 min. The cloud-top temperature is about 258 K, with temperatures above freezing in the lowest 500 m.

To test the new approach for ice microphysics (hereafter referred to as the “new scheme”), we have also developed a version of the scheme that uses the traditional approach for conversion of ice/snow to graupel following Rutledge and Hobbs (1984; hereafter RH84); hereafter, this version is referred to as the “traditional scheme”. In this scheme there are four prognostic ice variables: ice/snow mixing ratio and number concentration, and graupel mixing ratio and number concentration. This scheme requires threshold rain/snow/cloud droplet mixing ratios for the conversion of snow to graupel during riming. The sensitivity of the traditional scheme to these threshold mixing ratios is described in the next section.

4. RESULTS

Model results are generally similar when using either the traditional or new scheme, but there are significant differences. Time-height plots of the maximum cloud droplet, rain, ice/snow, and graupel mixing ratios in the horizontal at a given level are shown in Figs. 1 and 2 for the traditional and new schemes, respectively. Cloud water is produced in both simulations as the updraft increases in strength between \(t = 0\) and 25 min. Significant amounts of ice are produced by the time of the maximum updraft (\(t = 25\) min) through deposition/condensation-freezing nucleation as well as droplet freezing.

The noisy pattern seen in the ice and graupel mixing ratios using the traditional scheme in Fig. 1 likely reflects the thresholding behavior of graupel conversion. As the updraft weakens after \(t = 25\) min, a shaft of ice precipitation develops and partially melts near the surface. The cloud water is rapidly glaciated throughout most of the cloud layer, except near cloud top due to limited amounts of ice in this region. The separation of ice/snow and graupel into different categories using the traditional approach produces two shafts of ice precipitation and associated maxima of surface precipitation rate consisting of either graupel or ice/snow (see Figs. 1).

Since the traditional approach converts ice/snow to graupel in a single step, rapid conversion to graupel occurs once the threshold conditions are met, and this shaft of graupel precipitates rapidly.
to the surface with mean fallspeeds greater than 1.5 m s$^{-1}$. Significant surface precipitation (consisting of both graupel and rain) begins at $t = 30$ min in this run and produces a sharp peak in the precipitation rate at $t = 40$ min (Fig. 3). A secondary peak in the surface precipitation rate occurs at about $t = 80$ min associated with the weaker shaft of ice precipitation consisting of ice/snow. Because of the much slower particle fallspeeds associated with the ice/snow category (about 0.5 - 1 m s$^{-1}$) relative to graupel, much of this shaft does not reach the surface by the end of the simulation at $t = 90$ min (see Fig. 1).

Figure 3: Time evolution of domain-average cloud liquid water path (LWP), ice water path (IWP), droplet optical depth ($\tau_c$), ice optical depth ($\tau_i$), total cloud optical depth ($\tau_{tot}$), and surface precipitation rate (PREC). NEW and TRAD refer to simulations using the new and traditional ice microphysics schemes, respectively. TH-HIGH and TH-LOW refer to sensitivity tests using the traditional scheme but the threshold ice/snow and droplet mixing ratios for graupel production increased or decreased, respectively.

In contrast, the new scheme produces a single shaft of ice precipitation; its formation is also slightly delayed relative to the main precipitation shaft produced by the traditional scheme (see Fig. 2 and 3). Similarly to the traditional scheme, weak surface precipitation continues up to the end of the simulation, but in contrast there is not a distinct second peak in precipitation rate. Ice mixing ratio is primarily grown by vapor deposition initially; rimed mass fraction exceeding 90% occurs 10-20 min after the first appearance of the ice (see Fig. 4).

Rimed mass fraction steadily decreases after about $t = 45$ min corresponding to the reduction of droplet mixing ratio and hence decrease in the riming rate and accumulated rime mass. Since the shaft of ice precipitation consists of a mixture of partially-rimed crystals and graupel, the mean particle fallspeed is slightly less than that for a population consisting solely of graupel. Thus, this shaft of precipitation falls slower than the graupel shaft in the simulation using the traditional scheme, and significant precipitation does not reach the surface until about $t = 35$ min, a delay of about 5 min compared to the run with the traditional scheme (see Fig. 3). The peak surface precipitation rate is similarly delayed by about 5 min. Moreover, the new scheme produces significantly more cloud liquid water than the traditional scheme, especially after $t = 45$ min. These differences are also evident for the time- and domain-average values of LWP, optical depths, and surface precipitation rate (not shown). For ice optical depth, the difference is more significant, even though the ice water path is only somewhat smaller using the new scheme. This appears to reflect the fact that dense, heavily-rimed crystals in the new scheme have a relatively large ratio of mass to projected area (i.e., larger effective radius) compared to the unrimed crystals in the traditional scheme. Similar differences are apparent for the simulations with maximum updraft velocity of 2 m s$^{-1}$.

Simulations using the traditional scheme exhibit strong sensitivity to the assumed ice/snow and cloud water threshold mixing ratios required for conversion to graupel during riming of snow. Two
tests demonstrate this sensitivity. In the first test, conversion to graupel during collection of droplets is allowed only when both the ice/snow and droplet mixing ratios exceed 1 g/kg, compared to thresholds of 0.1 and 0.5 g/kg for ice/snow and droplets, respectively, for the baseline run using the traditional scheme (as well as in RH84). In the second test, conversion to graupel during collection of droplets occurs when any ice/snow and droplet mixing ratio is present (i.e., thresholds are set to zero). Note that results are not sensitive to the mixing ratio thresholds for conversion to graupel during rain-snow collisions because the formation of graupel is dominated by collisions between ice/snow and cloud droplets. A similar result was noted by RH84 in simulations of cold-frontal rainbands.

As expected, increasing the threshold ice/snow and droplet mixing ratios to 1 g/kg decreases the amount of graupel. Since particles fallspeeds for ice/snow are much slower than they are for graupel, ice mass is removed relatively slowly from the cloud. This leads to much larger values of IWP and rapid depletion of cloud liquid water through droplet collection and the diffusional growth of the ice field (see Fig. 3). It also leads to a smaller initial peak in the surface precipitation rate (at about t = 41 min) and much larger second peak (at t = 80 min) relative to the baseline run using the traditional scheme. Not surprisingly, reducing the threshold mixing ratios for graupel production leads to an increase in the LWP and decrease in the IWP relative to baseline due to faster removal of cloud ice. Despite large changes in the ice and liquid water paths, the total cloud optical depth is similar to baseline. Thus, the traditional approach produces a larger total cloud optical depth than the new scheme regardless of values specified for the threshold mixing ratios for graupel production. This suggests that simple tuning of the threshold mixing ratios in the traditional approach will not be able to reproduce results using the new scheme; even if such tuning were possible, it would likely be case-dependent.

5. SUMMARY AND CONCLUSIONS

This paper documents a novel approach for representing the ice-phase microphysics in numerical models. It includes only a single species of ice but retains the history of rimed mass fraction, in contrast to the traditional approach of separating ice into several distinct categories (e.g., cloud ice, snow, graupel). The new approach allows for a physically-based representation of the conversion of cloud ice into snow due to diffusional growth and aggregation, and the conversion of cloud ice and snow into graupel due to riming. The conceptual model of Heymsfield (1982) is applied for the latter. The history of rimed mass fraction in the new scheme is retained by predicting two ice mixing ratio variables: the mixing ratio acquired through water vapor deposition and the mixing ratio acquired through riming. The scheme was applied in a 2D kinematic modeling framework mimicking a mixed-phase shallow cumulus. The new scheme was compared against a version that included the traditional approach for graupel conversion processes following RH84. Significant differences were apparent between the new and traditional approaches, especially in terms of precipitation at the surface and the cloud radiative properties. In the traditional approach, threshold mixing ratios must be reached before graupel production is allowed during riming. The values specified for these thresholds are arbitrary and have little physical basis. Results using the traditional scheme exhibited strong sensitivity to these thresholds.

Future work will focus on testing the scheme within a 3D dynamic framework over a range of different conditions (e.g., deep convection, synoptic cirrus, mixed-phase stratocumulus), including comparison with observations, as well as looking at the impact of ice microphysics on the cloud dynamics. Application of the new approach to a detailed bin ice microphysics model is also currently under development.

BIBLIOGRAPHY


Acknowledgments.
This work was partially supported by the NOAA Grant NA05OAR4310107 and the NSF Science and Technology Center for Multi-Scale Modeling of Atmospheric Processes (CMMAP), managed by Colorado State University under cooperative agreement ATM-0425247. The National Center for Atmospheric Research is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation.