Process-Tracking Scheme Based on Bulk Microphysics to Diagnose the Features of Snow Particles

Akihiro Hashimoto¹, Hiroki Motoyoshi², Narihiro Orikasa¹, and Ryohei Misumi²

¹Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan
²National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan

Abstract

We have developed a new method of diagnosing the characteristics of ice particles using a bulk microphysics model. Our model tracked the mass compositions of different classes of ice particles, using their microphysical process of origin, such as water vapor deposition and riming. The mass composition from depositional growth was further divided into six components by the temperature and humidity ranges corresponding to the typical growth habits of ice crystals. In test simulations, the new framework successfully revealed the influences of riming and depositional growths of ice particles within clouds and on surface snowfall. The new approach enables weather prediction models to provide much more information on the characteristics of ice particles regarding crystal habits and the extent of riming.

(Citation: Hashimoto, A., H. Motoyoshi, N. Orikasa, and R. Misumi, 2020: Process-tracking scheme based on bulk microphysics to diagnose the features of snow particles. SOLA, 16, 51–56, doi:10.2151/sola.2020-009.)

1. Introduction

During the last decade, new microphysical models were developed to incorporate the various physical properties of solid hydrometeors. Hashino and Tripoli (2007, 2008, 2011a, 2011b) developed a sophisticated spectral-bin microphysics model that represents variations in ice crystal habits, based on Chen’s (1992) model. Brdar and Seifert (2018) developed a Monte-Carlo particle model to represent riming and aggregation of ice particles. Shima et al. (2019) extended their superdroplet method (Shima et al. 2009), which is a particle-based, probabilistic simulation model of cloud microphysics, to include mixed-phase microphysics.

Recent advances in computational power enable such models to work under realistic atmospheric conditions, although the computational cost for this remains unfeasibly high. Bulk microphysics models provide a cheaper alternative to spectral-bin and particle-based models. Over the last few decades, developments and improvements have been made to bulk microphysics models to better understand the mechanisms of a cloud and precipitation system, and thus improve numerical weather forecasting (Lin et al. 1983; Reisner et al. 1998; Stoeilinga et al. 2003; Morrison and Milbrandt 2015).

The capability of a bulk microphysics model to represent the various properties of solid hydrometeors and mixed-phase microphysical processes improves when one increases the number of classes of ice particles, hydrometeors, and the number of prognostic variables implemented in each class. Typically, most modeling studies have adopted visually distinguishable particle types as classes and physically observable properties as variables. Two strategies have been implemented to produce more sophisticated bulk microphysics models: (i) the multiclass strategy adds a new hydrometeor class and (ii) the multivariable strategy adds one or more variables to a hydrometeor class.

Using the multiclass strategy, Lin et al. (1983) added a new class for snow to Orville and Kopp’s (1977) model, which had four classes – cloud water, rain, cloud ice, and hail – and solved a time evolution equation for the mixing ratio for each class (namely a single-moment scheme). Their work established the basic system of hydrometeor classification that is still used in bulk microphysical modeling. Currently, many bulk microphysical models have five or six classes of hydrometeor.

Using the multivariable strategy, Reisner et al. (1998) solved time evolution for the number concentration in every class of solid hydrometeor in addition to the mixing ratio (namely a double-moment scheme) to diagnose the volume-mean size of a solid hydrometeor, which is crucial to accurately calculating microphysical processes. Milbrandt and Yau (2005) proposed a triple-moment microphysics scheme that solved the time evolution of the sixth moment of the size distribution function, in addition to the mixing ratio and particle number concentration in each class, to determine a new size distribution parameter associated with the dispersion of particle size with the goal of obtaining more accurate solutions for the microphysical equations. Recalling that the number concentration and mixing ratio are essentially interpreted as the zeroth and third moments of the number size distribution function, respectively, developments using the multivariable strategy were limited in improving the diagnostic method for the size distribution parameters until the work of Milbrandt and Yau (2005).

Morrison and Grabowski (2008, hereafter MG08) proposed a new concept for bulk microphysics modeling. They adopted a single-class framework of ice, instead of using the traditional classification system. The mixing ratio for ice was divided into that originating from vapor deposition and that from riming. They were tracked separately, which enables us to know quantitatively the contributions from particular microphysical processes to the predicted characteristics of ice particles. Further developments were made to their model (Morrison and Milbrandt 2015, hereafter MM15), creating new trends in the numerical simulation of a cloud and precipitation system (Morrison et al. 2015; Milbrandt and Morrison 2016).

In our new approach, we developed a bulk microphysics module in the Japan Meteorological Agency Non-Hydrostatic Model (JMA-NHM; Saito et al. 2006) to examine the characteristics of solid hydrometeors in much more detail. We adopted a multivariable strategy, by adding several new variables representing microphysical processes to hydrometeor classes, as was done in the MG08 and MM15 models, but the development enables us to diagnose ice crystal growth habits within the traditional classifications. Although, the currently diagnosed characteristics do not influence the original solution of microphysical equations (including gravity sedimentation and collision efficiency), the new approach potentially expands the applicability of the bulk microphysics model in research collaborations with microphysical observations. The results from our test simulations using the improved JMA-NHM demonstrate the effectiveness of our approach.

2. Modeling

2.1 Numerical model

We applied the JMA-NHM to our numerical experiments, using the original configuration with the following exceptions.
First, we adopted a double-moment scheme for all classes of solid hydrometeors, such as cloud ice, snow, and graupel, while the original configuration adopts a double-moment scheme only for cloud ice and a single-moment scheme for the other hydrometeors such as snow and graupel (Ikawa and Saito 1991). For liquid hydrometeors (such as cloud water and rain), we adopted a single-moment scheme to predict only the mixing ratio of particles. Second, we removed the original configuration’s ice-saturation adjustment scheme (Tao et al. 1989) to avoid the unrealistic formation of ice clouds in the upper troposphere (Hashimoto et al. 2007). Third, we removed a cumulus parameterization. Finally, we implemented a cloud ice, snow and graupel, respectively. These are the original hydrometeor classes in the JMA-NHM. Orange shows the riming growth mode for cloud ice or snow. Other colors show the depositional growth modes of cloud ice or snow: blue, irregular needle; sky blue, needle/scroll/cup/column; light green, sector/plate; green, dendritic; and yellow, column. Gray represents all the others including irregular types, which appear at low temperatures.

Here, $S$ is defined as $(Q_s + Q_e)/Q_{aci}$, where $Q_s$, $Q_e$, and $Q_{aci}$ are the mixing ratios of cloud water, water vapor, and saturated water vapor with respect to ice, respectively. By using the expression $P_{adv}$ in Ikawa and Saito (1991), the PRD is defined for the depositional growth as follows:

$$\text{PRD}(Q_{aci}) = \begin{cases} P_{adv} & (\text{Dep}, \text{irregular needle}) \\ P_{adv} & (\text{Dep}, \text{needle/scroll/cup/column}) \\ P_{adv} & (\text{Dep}, \text{sector/plate}) \\ P_{adv} & (\text{Dep}, \text{dendritic}) \\ P_{adv} & (\text{Dep}, \text{other habits}) \end{cases},$$

where $x = i, s$, and $g$. For ice nucleation, PRD is defined by the same stratification as shown above. Figure 1 shows these subclasses with colors representing the class of cloud ice or snow. The effects of ice nucleation on the mass of solid hydrometeors are quite small compared with the effects of riming and deposition. Therefore, for the sake of simplicity, in this study, we will show only the results associated with riming and deposition. The classification of the addressed riming and depositional growth processes is summarized in Table 1.

3. Numerical simulations

Test simulations were conducted in a two-dimensional domain. The domain measured 600 km horizontally and 12.6 km vertically (Fig. 2a). The domain contained a 1500-m-high and 150-km-wide bell-shaped mountain centered at $x = 400$ km. Horizontal grid spacing was 1 km, and the vertical grid spacing was 300 m. We used 48 vertical layers in a terrain-following coordinate system. The timestep was 4 s. We performed 13 simulations. The initial times are listed in Table 2. The integration time was 60 h, which included a period of snowfall events observed in the Echigo mountains (37°03′19.9″N, 139°00′11.4″E) during January 1995 (Harimara and Nakai 1999). Initial conditions for the simulations, air temperature, and relative humidity profiles for the middle of Sea of Japan [$40°N, 135°E$] are taken from the JRA-55 reanalysis data (Kobayashi et al. 2015) for each timestep listed in Table 2. A horizontal wind of 10 m s$^{-1}$ toward the right (Fig. 2b) was applied across the domain at the beginning of every simulation. It was
applied at the upwind boundary throughout each simulation. The surface fluxes of heat and humidity were given according to surface states (sea, blue; land, green; and snow cover, white in Fig. 2a). Output data were available every 10 min from the surface and every 60 min from the atmosphere.

4. Results

Figure 2a shows an example of the results on accumulated precipitation amount from the forecast time (FT) of 36 to 60 h...
in the simulation with an initial time of 15:00 JST on 17 January 1995.

Graupel (red) shows a large contribution to the total amount of precipitation over the sea and near the coast. This is consistent with the statistical analysis of Mizuno (1992). Moving inland, the contribution of graupel decreases, and components of riming (orange) and deposition (blue, sky blue, light green, or green) growth of snow increase. This means that partially rimed snow becomes the major contributor to snowfall. On the lee side of the mountain, most of the snowfall originates from depositional growth. The depositional growth at temperatures from −20°C to −10°C (green or light green) shows the largest contribution over the top or lee side of the mountain.

Figure 2b shows the averaged in-cloud characteristics for the same period as in Fig. 2a. Graupel (red) and the component of riming growth of cloud ice and snow \(Q_{\text{Dep},i} + Q_{\text{Dep},s}\) show a large contribution among solid hydrometeors over the sea \((x = 180\) and 280 km) and the upwind side of the mountain \((x = 370\) km). The columnar deposition over both warm \(Q_{\text{Dep},i} + Q_{\text{Dep},s}\) \(i\) \((i = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14)\) and cold \(Q_{\text{Dep},i} + Q_{\text{Dep},s}\) \(s\) \((s = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14)\) temperature ranges has a part of the mass of cloud ice and snow over the upwind side of the mountain \((x = 370\) km). The dendritic growth mode \(Q_{\text{Dep},i} + Q_{\text{Dep},s}\) \(i\) \((i = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14)\) shows a large contribution around −15°C over the upwind \((x = 370\) km) where updraft and downburst, and consequently, ice supersaturation increases.

Implementation of the formulations described in Section 2.2 successfully revealed the microphysical characteristics of surface snowfall and solid hydrometeors in snow clouds. In general, this kind of data has not been produced using numerical weather prediction models before. One of the practical benefits of this improvement is to reveal the temporal-spatial distribution of particular types of snow particles that increase the risk of snow avalanche (Hirashima et al. 2018).

5. Discussion

In this section, we confirm the validity of the microphysical features simulated by the new microphysical data.

5.1 Riming proportion in surface snowfall

Harimaya and Nakai (1999) used data obtained during seven snowfall events in January 1995 (Fig. 3a) to show the relationship between snowfall intensity and riming proportion (the ratio of riming mass to total mass constituting a solid hydrometeor Supplemental material S1). They stated that:

Although the riming proportion varies greatly when the snowfall intensity is weak, the lower limit of the riming proportion tends to increase, and the blank space without solid points tends to expand with an increase in snowfall intensity. Therefore, stronger snowfall intensity does not occur when there is a low riming proportion.

In other words, weak riming suppresses large snowfall rates.

Figure 3b shows scatter plots of the same parameters but obtained from simulations. The lower limit of the simulated riming proportion increases with increasing snowfall intensity, as in the observed result. However, the upward variability of the simulated riming proportion (Fig. 3b) is smaller than the observed result (Fig. 3a), especially when there is intense snowfall.

These results show that the model can reproduce the observed feature: weak riming suppresses large snowfall rates, but the riming rate is underpredicted in the model as snowfall intensifies. The modeled riming rate is quite sensitive to the rate of ice nucleation. A large ice nucleation rate tends to suppress the riming rate because the generated ice crystals consume cloud droplets through the Bergeron–Findeisen process. Currently, the ice nucleation process is not well understood. More study through a combination of field observation, laboratory experimentation, and modeling is required to understand its impact.

5.2 Depositional growth mode of ice particles

The microphysical characteristics of winter orographic snow clouds were observed by a hydrometeor videosonde (HYVIS, Orikasa and Murakami 1997) launched from the upwind side of the Echigo mountains in Japan for 9 years from 1994 to 2002. The shape, maximum dimension, and water content of hydrometeors were derived from detected images (Supplementary material S2). Figures 4a, 4b, and 4c show the observed relationships between temperature and the mass content of different crystal habits. A columnar crystal (Fig. 4a) shows double peaks \((−5°C\) and \(−25°C\)) in the mass content profile. A dendritic crystal (Fig. 4b) shows a maximum from −15°C to −10°C, and a planar crystal (Fig. 4c) shows a relatively flat profile. Figures 4d, 4e, and 4f provide the corresponding simulation results at \(x = 370\) km, which mimics the HYVIS launching site. The simulated mass content of the columnar growth mode (Fig. 4d) shows double peaks \((−9°C\) and \(−23°C\)) as in the observation result. The peak at the colder temperature originates from crystal growth in the temperature range from −36°C to −20°C (yellow in Fig. 1). The peak at the warmer temperature originates from crystal growth in the temperature range from −10°C to −4°C (sky blue in Fig. 1). Profiles for the dendritic (Fig. 4e) and planar (Fig. 4f) growth modes show almost the same characteristics as in the observed profiles at temperatures warmer than −20°C. The peak around −15°C in Fig. 4e comes from the crystal growth under the condition of \(−17°C < T < −14°C\) and \(S > 7\%\) (green in Fig. 1). In contrast, for temperatures below −20°C, these profiles show a sharp decrease with increasing altitude (Figs. 4e and 4f), while the observed profiles show a gentle decrease (Figs. 4b and 4c). The classification of partial mass originating from depositional growth in our model currently follows Nakaya’s \(T_s - S\) diagram (Nakaya 1954), where columnar crystals are predicted below −20°C. Bailey and Hallet (2004, 2009, 2012) reviewed crystal habits in the temperature range from −20°C to −70°C based on their laboratory experiment and in-situ observation. They gave examples showing that many plate-like crystals were observed below −20°C, in contrast to Nakaya’s diagram. In light of this, the discrepancy between the observation and simulation may indicate the necessity of updating our classification method. To renew this model in the near future, we will consider newer work, such as Bailey and Hallet (2004, 2009, 2012) and Takahashi (2014, 2018).

6. Conclusion

In this article, we proposed a new bulk microphysics framework to examine the microphysical properties of ice particles in the atmosphere. We demonstrated its effectiveness in an investigation of the microphysical features of a cloud and precipitation...
system. In the simulations, the new framework successfully revealed the influence of the riming and depositional growth processes not only on the mass of ice particles suspended in the atmosphere, but also on snowfall at the ground surface. The simulations reproduced the relationship between the riming proportion and snowfall: that a larger snowfall rate on the ground requires more active riming in a cloud. However, the simulations failed to reproduce a large variation of riming proportions. One of the explanations for this is the uncertainty regarding the parameterization of ice nucleation. The simulated mass content profiles for the different depositional growth modes of ice crystals essentially concurred with those obtained by balloon-borne measurements. For thoroughness of modeling, our model needs the implementation of microphysical feedback reflecting the diagnosed characteristics of hydrometeors into the original equations. The proposed approach provides a new perspective on the validation of a bulk microphysics model using microphysical observations.

Acknowledgements

This work was supported in part by the Japan Society for the Promotion of Science, KAKENHI Grant Number JP16K01340, JP16KO5557, JP17K18453, and JP19K04978. We would like to thank the editor and two anonymous reviewers for their constructive comments and suggestions.

Edited by: H. Iwabuchi

Supplementary materials

S1. Riming proportion
S2. Water content profile of ice crystals
S3. Computational time

References

Bailey, M., and J. Hallet, 2004: Growth rates and habits of ice crystals between −20° and −70°C. J. Atmos. Sci., 61, 514–544.

Bailey, M., and J. Hallet, 2009: A comprehensive habit diagram for atmospheric ice crystals: Confirmation from the laboratory, AIRS II, and other field studies. J. Atmos. Sci., 66, 2888–2899.

Bailey, M., and J. Hallet, 2012: Ice crystal linear growth rates from −20° and −70°C: Confirmation from wave cloud studies. J. Atmos. Sci., 69, 390–402.

Brdar, S., and A. Seifert, 2018: McSnow: A Monte-Carlo particle model for riming and aggregation of ice particles in a multi-dimensional microphysical phase space. J. Adv. Model. Earth Syst., 10, 187–206, doi:10.1002/2017MS001167.

Chen, J.-P., 1992: Numerical simulation of the redistribution of atmospheric trace chemicals through cloud processes. Ph.D. thesis, The Pennsylvania State University, 343 pp.

Davis, C. I., 1974: Ice nucleating characteristics of various AgI aerosols. Ph.D. thesis, University of Wyoming, 259 pp.

Harimaya, T., and M. Sato, 1989: Measurement of the riming amount on snowflakes. J. Fac. Sci., Hokkaido Univ., Ser. VII (Geophysics), 8, 355–366.

Harimaya, T., and Y. Nakai, 1999: Riming growth process contributing to the formation of snowfall in orographic areas of Japan facing the Japan Sea. J. Meteor. Soc. Japan, 77, 101–115, doi:10.2151/jmsj1965.77.1_101.

Hashimoto, A., M. Murakami, T. Kato, and M. Nakamura, 2007: Evaluation of the influence of saturation adjustment with respect to ice on meso-scale model simulations for the case of 22 June, 2002. SOLA, 3, 85–88, doi:10.2151/sola.2007-022.

Hashino, T., and G. J. Tripoli, 2007: The Spectral Ice Habit Prediction System (SHIPS). Part I: Model description and
Kobayashi, S., 1961: The growth of snow crystal at low supersaturation.

Hashino, T., and G. J. Tripoli, 2008: The Spectral Ice Habit Prediction System (SHIPS). Part II: Simulation of nucleation and depositional growth of polycrystals. J. Atmos. Sci., 65, 3071–3094.

Hashino, T., and G. J. Tripoli, 2011a: The Spectral Ice Habit Prediction System (SHIPS). Part III: Description of the ice particle model and the habit-dependent aggregation model. J. Atmos. Sci., 68, 1125–1141.

Hashino, T., and G. J. Tripoli, 2011b: The Spectral Ice Habit Prediction System (SHIPS). Part IV: Box model simulations of the habit-dependent aggregation process. J. Atmos. Sci., 68, 1142–1161.

Hiirishima, H., S. Yamaguchi, K. Nakamura, and A. Hashimoto, 2018: Approaches of avalanche predictions resulting from non-rimed falling snow crystals using the SNOWPACK model. Proc. International Snow Science Workshop, Innsbruck, Austria, 962–966.

Ikawa, M., and K. Saito, 1991: Description of a non-hydrostatic model developed at the Forecast Research Department of the MRI. Technical reports of the Meteorological Research Institute, 28, 238 pp. (Available online at https://www.mri-jma.go.jp/Publish/Technical/DATA/VOL_28/28_en.html, accessed 5 November 2019)

Kobayashi, S., 1961: The growth of snow crystal at low supersaturation. Phil. Mag., 6, 1363–1370.

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyao, and K. Takahashi, 2015: The JRA-55 reanalysis: General specifications and basic characteristics. J. Meteor. Soc. Japan, 93, 5–48, doi:10.2151/jmsj.2015-001.

Lin, Y. L., R. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. J. Climate Appl. Meteor., 22, 1065–1092.

Milbrandt, J. A., and M. K. Yau, 2005: A multimoment bulk microphysics parameterization. Part II: A proposed three-moment closure and scheme description. J. Atmos. Sci., 62, 3065–3081.

Milbrandt, J. A., and H. Morrison, 2016: Parameterization of cloud microphysics based on the prediction of bulk ice particle properties. Part III: Introduction of multiple free categories. J. Atmos. Sci., 73, 975–995.

Mizuno, H., 1992: Statistical characteristics of graupel precipitation over the Japan islands. J. Meteor. Soc. Japan, 70, doi:10.2151/jmsj1965.70.1_115.

Morrison, H., and W. W. Grabowski, 2008: A novel approach for representing ice microphysics in models: Description and tests using a kinematic framework. J. Atmos. Sci., 65, 1528–1548.

Morrison, H., and J. A. Milbrandt, 2015: Parameterization of ice microphysics based on the prediction of bulk particle properties. Part I: Scheme description and idealized tests. J. Atmos. Sci., 72, 287–311, doi:10.1175/JAS-D-14-0065.1.

Morrison, H., J. A. Milbrandt, G. H. Bryan, K. Ikeda, S. A. Tessendorf, and G. Thompson, 2015: Parameterization of cloud microphysics based on the prediction of bulk ice particle properties. Part II: Case study comparisons with observations and other schemes. J. Atmos. Sci., 72, 312–339, doi:10.1175/JAS-D-14-0066.1.

Murakami, M., and T. Matsuo, 1990: Development of the hydrometeor videosonde. J. Atmos. Ocean. Tech., 7, 613–620.

Nakaya, U., 1954: Snow Crystals: Natural and Artificial. Harvard University Press, 510 pp.

Orikasa, N., and M. Murakami, 1997: A new version of hydrometeor videosonde for cirrus cloud observations. J. Meteor. Soc. Japan, 75, 1033–1039.

Orville, H. D., and F. J. Kopp, 1977: Numerical simulation of the life history of a hailstrom. J. Atmos. Sci., 34, 1596–1618.

Reisner, J., R. M. Rasmussen, and R. T. Bruintjes, 1998: Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. Quart. J. Roy. Meteor. Soc., 124, 1071–1107.

Saito, K., T. Fujita, Y. Yamada, J. Ishida, Y. Kumagai, K. Aramaki, S. Ohmori, R. Nagasawa, S. Kumagai, C. Muroi, T. Kato, H. Eito, and Y. Yamazaki, 2006: The operational JMA non-hydrostatic mesoscale model. Mon. Wea. Rev., 134, 1266–1297.

Shima, S., K. Kusano, A. Kawano, T Sugiyama, and S. Kawahara, 2009: The super-droplet method for the numerical simulation of clouds and precipitation: A particle-based and probabilistic microphysics model coupled with a non-hydrostatic model. Quart. J. Roy. Meteor. Soc., 135, 1307–1320, doi:10.1002/qj.441.

Shima, S., Y. Sato, A. Hashimoto, and R. Misumi, 2019: Predicting the morphology of ice particles in deep convection using the super-droplet method: development and evaluation of SCALE-SDM 0.2.5-2.0/2.2.1. Geosci. Model Dev. Discuss., in review, doi:10.5194/gmd-2019-294.

Stoelinga, M. T., and co-authors, 2003: Improvement of microphysical parameterization through observational verification experiment. Bull. Amer. Meteor. Soc., 84, 1807–1826, doi:10.1175/BAMS-84-12-1807.

Takahashi, T., 2014: Influence of liquid water content and temperature on the form and growth of branched planar snow crystals in a cloud. J. Atmos. Sci., 71, 4127–4142, doi:10.1175/JAS-D-14-0043.1.

Takahashi, T., 2018: Supercooled cloud tunnel studies on the growth of branched planar snow crystals below water saturation. AMS 15th Conf. on Cloud Physics, 105, 9 July 2018, Vancouver, Canada. (Available online at https://ams.confex.com/ams/15CLOUD15ATRAD/meetingapp.cgi/Paper/347181, accessed 5 November 2019)

Tao, W.-K., J. Simpson, and M. McCumber, 1989: An ice-water saturation adjustment. Mon. Wea. Rev., 117, 231–235.