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The Cloud Processes of a Simulated Moderate Snowfall Event in North China

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ABSTRACT

The understanding of the cloud processes of snowfall is essential to the artificial enhancement of snow and the numerical simulation of snowfall. The mesoscale model MM5 is used to simulate a moderate snowfall event in North China that occurred during 20–21 December 2002. Thirteen experiments are performed to test the sensitivity of the simulation to the cloud physics with different cumulus parameterization schemes and different options for the Goddard cloud microphysics parameterization schemes. It is shown that the cumulus parameterization scheme has little to do with the simulation result. The results also show that there are only four classes of water substances, namely the cloud water, cloud ice, snow, and vapor, in the simulation of the moderate snowfall event. The analysis of the cloud microphysics budgets in the explicit experiment shows that the condensation of supersaturated vapor, the depositional growth of cloud ice, the initiation of cloud ice, the accretion of cloud ice by snow, the accretion of cloud water by snow, the deposition growth of snow, and the Bergeron process of cloud ice are the dominant cloud microphysical processes in the simulation. The accretion of cloud water by snow and the deposition growth of the snow are equally important in the development of the snow.

Key words: snowfall, cloud microphysics parameterization, cumulus parameterization, MM5, North China

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1. Introduction

The cloud process plays an important role in all precipitation. The adequate representation of the cloud process has become one of the most challenging tasks in mesoscale modeling. Based on the grid resolution of numerical models, one may divide the treatments of cloud processes in a mesoscale model into two categories: the cumulus parameterization (implicit) and the parameterization of the microphysical process (explicit). The performance of four cumulus parameterization schemes, namely the Anthes-Kuo scheme (Anthes, 1983), Betts-Miller scheme (Betts-Miller, 1986), Grell scheme (Grell, 1993), and Kain-Fritsch scheme (Kain and Fritsch, 1993), were examined using six precipitation events over the continental United States in both cold and warm seasons with the Pennsylvania State University-National Center for Atmospheric Research (Penn State/NCAR) nonhydrostatic Mesoscale Model (MM5) by Wang and Seaman (1997). They and others (e.g., Kuo et al., 1996; Yang et al., 2000; Yang and Tung, 2003) found that none of the current cumulus parameterization schemes outscore the others and each seems to have some systematic errors though the convection needs to be parameterized. Lin et al. (2000) also evaluated the resolvable-scale microphysics schemes in the simulation of heavy rain that occurred in the southern part of the Yangtze River and found the relative systematic errors may be 10%–30% by using the various resolvable-scale microphysics schemes.

We try to understand how and to what degree the treatments of the cloud processes work in a moderate snowfall event in North China in this study. Since the snowfall results from the cold cloud precipitation, its cloud processes might be different from those of the tropical and mid-latitude summer precipitation. Furthermore, the understanding of the cloud processes of

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snowfall is essential to the artificial snow enhancement in North China (Sun et al., 2003). In the aircraft operations arena, the cloud microphysical processes are critical to the prediction of airframe icing (Cober et al., 2001). Reisner et al. (1998) and Thompson et al. (2004) used a double-moment microphysical scheme to improve explicit, real-time winter precipitation forecasts of supercooled liquid water and aircraft icing. Thus, the accurate parameterization of cloud processes is of fundamental importance in the numerical simulation of snowfall.

In this study, the Penn State National Center of Atmospheric Research (NCAR) Mesoscale Model MM5 (Grell et al., 1994) is used to simulate the cloud process of a moderate snowfall event. Thirteen experiments with different cumulus parameterization schemes and different options of the cloud microphysical parameterization schemes are carried out and the results are compared with each other. The main purpose is to test the performances of the cloud microphysical parameterization schemes in the simulation of a moderate snowfall event that occurred in North China and to determine its dominant cloud microphysics processes.

2. Model and experiment design

The Penn State/NCAR MM5 was used to simulate the moderate snowfall event from 0000 UTC 20 December to 0000 UTC 21 December 2002 in North China. The control experiment (CTL) domain includes two domains (D01 and D02) which are run in a two-way interactive mode, as shown in Fig. 1. On a Lambert conformal map, the coarse domain (D01) covers 88×97 grid points with a grid length of 54 km. The central latitude and longitude are 42°N and 114°E, respectively. The fine domain (D02) has 97×97 grid points with a grid length of 18 km. Vertically, the MM5 model uses a terrain-following σ coordinate, $\sigma = (p_0 - p_{\rm t})/(p_{\rm s}^* - p_{\rm t})$, where p_0 is the reference state pressure in the atmosphere, $p_{\rm s}^*$ is the reference surface pressure that is constant with time and depends on the height of the orography, and $p_{\rm t}$ is the atmospheric pressure at the top model level, which is 50 hPa. From the top to the surface level, there are 24 sigma levels (0.00, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, 0.60, 0.65, 0.70, 0.75, 0.80, 0.85, 0.89, 0.93, 0.96, 0.98, 0.99, 1.00). In the control experiment (CTL), the Grell cumulus parameterization scheme (Grell et al., 1994), the Goddard Cumulus Ensemble (GCE) model cloud microphysics (Tao and Simpson, 1993; modified by Braun and Tao, 2000), the medium range forecast (MRF) PBL parameterization scheme (Hong and Pan, 1996) and NCAR Community Climate Model (CCM2) longwave and shortwave schemes (Hack et al., 1993) are used for the model physics in both the coarse and fine domains.

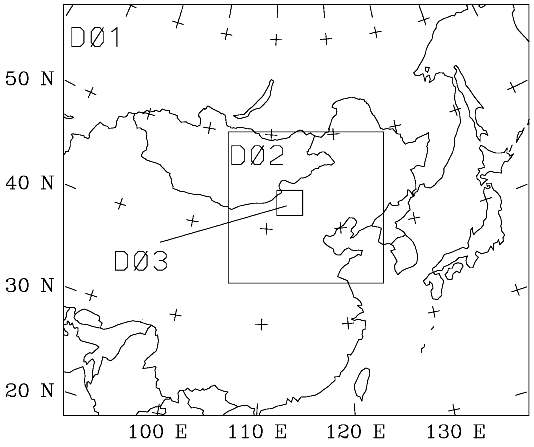

Fig. 1. Computational domains for the MM5 model.

The initial and boundary conditions are interpolated from the 1° × 1° resolution global reanalysis data from the National Center for Environmental Prediction (NCEP) onto the coarse model resolution (grid length of 54 km) and the vertical interpolation onto the 23 sigma levels. In order to reduce the initial imbalance of the model, the integrated mean divergence in a column is removed as well.

The CTL experiment is initialized at 0000 UTC 20 December 2002 and integrated for 24 hours. The time step is 120 (40) seconds for the coarse (fine) domain. As shown in Table 1, thirteen experiments are designed with different cloud physics in the fine domain (D02). In all experiments, the Goddard microphysical scheme, in which the cloud water, rain, cloud ice, snow, and graupel/hail are taken into account, is applied and modified. The Goddard scheme is a single-moment microphysical scheme that has a lower computational cost than the Reisner double-moment scheme (Reisner et al., 1998). In the first four experiments (CTL, KUO, KF, and BM), four cumulus parameterization schemes, namely the Grell scheme, Anthes-Kuo scheme, Kain-Fritsch scheme, and Betts-Miller scheme, are used with the Goddard microphysical scheme. In experiment NN, the Goddard microphysical scheme is simply used and no cumulus parameterization scheme is considered. Four experiments A1, A2, A3, and B1, are used to examine the simulation results in the absence of hail, graupel, rain or cloud water in the Goddard microphysical scheme. In experiments C1 and C2, the microphysical process of the cloud water is treated differently. Specifically, the processes of the deposition, accretion, and homogeneous freezing of the cloud water in the formation of the cloud ice, and the processes of the depositional growth and melting of the cloud ice in the formation of the cloud water are kept in experiment C1. However, the condensation of supersaturated vapor and the evaporation of the cloud water are not considered in

Table 1. Summary of the numerical experiments described in this study. All experiments are identical between each other, except for the options of cumulus parameterization and microphysics in the fine-grid simulation. "Yes1 indicates that there are the deposition of cloud water, the accretion of cloud water, homogeneous freezing of cloud water to form cloud ice, depositional growth of cloud ice at the expense of cloud water, and melting of cloud ice to form cloud water, but there is no condensation of supersaturated vapor or evaporation of cloud water. "Yes2 indicates that there are no other microphysical processes for cloud water but only the condensation of supersaturated vapor or evaporation of cloud water.

Experiment	Cumulus parameterization scheme	Goddard Cloud Microphysics parameterization schemes					
		Cloud water	Rain	Cloud ice	Snow	Graupel	Hail
CTL	Grell	Yes	Yes	Yes	Yes	Yes	No
KUO	Anthes-Kuo	Yes	Yes	Yes	Yes	Yes	No
KF	Kain-Fritsch	Yes	Yes	Yes	Yes	Yes	No
BM	Betts-Miller	Yes	Yes	Yes	Yes	Yes	No
NN	No	Yes	Yes	Yes	Yes	Yes	No
A1	Grell	Yes	Yes	Yes	Yes	No	Yes
A2	Grell	Yes	Yes	Yes	Yes	No	No
A3	Grell	Yes	No	Yes	Yes	Yes	No
B1	Grell	No	Yes	Yes	Yes	Yes	No
C1	Grell	Yes1	No	Yes	Yes	No	No
C2	Grell	Yes2	No	Yes	Yes	No	No
NN2	No	Yes2	No	Yes	Yes	No	No
HR	3-domain high resolution simulation with all microphysical processes						

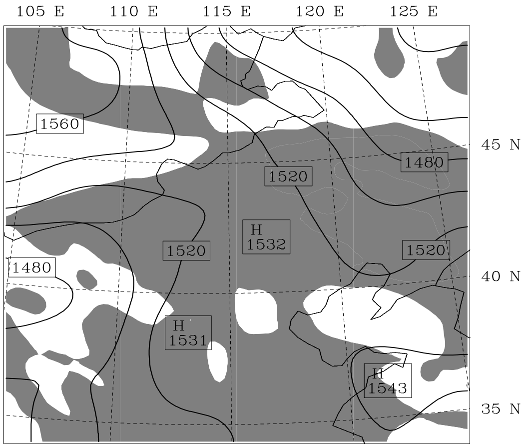

Fig. 2. 850-hPa geopotential height (unit: m) and 700-hPa horizontal advection of water vapor at 0000 UTC 20 December 2002. Shading denotes the positive horizontal advection region of water vapor. The contour interval of geopotential height is 20 m.

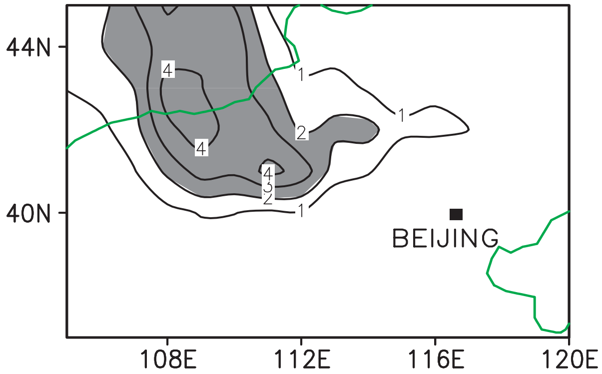

Fig. 3. The observed 24-hour accumulated snowfall (mm) from 0000 UTC 20 December to 0000 UTC 21 December 2002. Contours interval is 1 mm. Shading marks the region where the value exceeds 2 mm.

the C1 experiment. As a contrast, in experiment C2, the condensation of supersaturated vapor and the evaporation of cloud water are retained, but the other microphysical processes of cloud water are neglected. In experiment NN2, all the options are identical with experiment C2 except that there is no cumulus parameterization scheme. At last, we conducted experiment HR in order to determine the dominant cloud microphysics processes. Three domains are included in experiment HR in which the finest domain (D03) has 49×49 grid points with a grid length of 6 km and a time step of 13.33 s (Fig. 1).

3. Result and discussion

According to Meng (2003), a light and a moderate snowfall occurred successively in the eastern part of northwestern China and most parts of North China during the period from 19 to 24 December 2002. For six days, the residents of Beijing were able to enjoy the snow, which transformed the city into a white winter landscape. It was said to be the longest consecutive

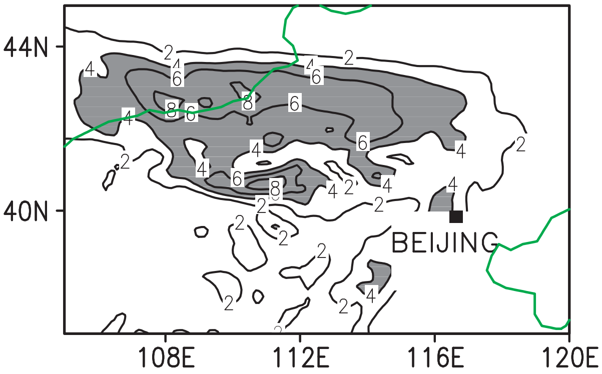

Fig. 4. Simulated 24-hour accumulated snowfall (mm) in the CTL experiment, valid from 0000 UTC 20 December to 0000 UTC 21 December 2002. Contours interval is 2 mm. Shading marks the region where the value exceeds 4 mm.

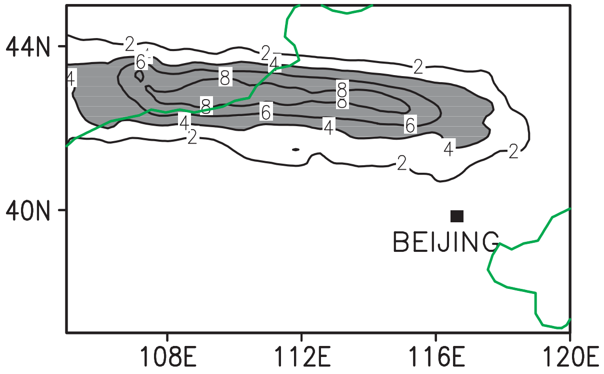

Fig. 5. As in Fig. 4, but for experiment B1.

snowfall for the city in the past 128 years (Meng, 2003). A brief synoptic description is given below. From 0000 UTC 20 December to 0000 UTC 21 December 2002, the cold high to the west of Lake Baikal forced the cold air to move eastward and southward, and water vapor was transported from the low latitudes because of the upside-down trough of the lower troposphere in the low latitudes (Fig. 2). This, then, it caused the continuous snowfall over the large area of North China. It is shown in Fig. 3 that there was a light and moderate snowfall observed in the central part of Inner Mongolia during the period. In comparison to the observations, the CTL simulations reproduced the snowfall distribution considerably well, as displayed in Fig. 4. However, the center of the maximum snowfall is too far to the north of the observed, the simulated snowfall amount is overestimated, and the simulated snowfall area is larger than the observed one.

All experiments except the experiment HR are categorized into two groups in terms of the simulation results on both the coarse domain (D01) and the fine domain (D02): the first group consists of the experiments CTL, KUO, KF, BM, NN, A1, A2, A3, C2, and NN2, while the second group consists of the experiments B1 and C1. In each group, the simulation results are almost identical among individual members. Specifically, according to the simulated snowfall pattern, the first group is characterized by the CTL experiment (Fig. 4), whereas the second group is characterized by the B1 experiment (Fig. 5). It can be seen that the two groups differ significantly.

First of all, the cumulus parameterization does not produce any precipitation in the fine domain (D02) for all experiments. The current approach to precipitation parameterization in MM5 is the hybrid approach (Zhang, 1998; Molinari and Dudek, 1992), which uses a subgrid-scale convective parameterization (the implicit scheme) to remove the convective instability and the resolvable grid-scale cloud microphysical parameterization of varying degrees of sophistication (the explicit scheme) to treat the cloud precipitation process on the convectively stable and nearly neutral layer. The former produces the sub-grid scale precipitation and the latter produces the grid-scale precipitation. The total precipitation is the sum of the two. The fact that no precipitation occurs from the cumulus parameterization schemes means that we can turn off the schemes (as in experiments NN and NN2) for the case of a moderate snowfall event in North China. Then, we can primarily focus on the resolvable-scale cloud microphysical parameterization (the explicit scheme).

Secondly, the simulated results of experiments A1, A2, and A3 are almost identical with that of the CTL experiment. This means that the microphysical processes for the rain, graupel or hail have little impact on the snowfall simulation. This suggests that there is no rain, graupel or hail in the simulation of a moderate snowfall event in North China.

Thirdly, the results of experiment B1 are different from those of the CTL experiment. The absence of cloud water results in larger systematic errors. In the Goddard microphysical scheme of MM5, when the temperature in the air is below the melting temperature, an iterative method different from Tao et al. (1989) is used in which the adjustment is first done for liquid water for temperatures warmer than 253 K, and then for ice only where the temperature is colder than 258 K.This means that the effect of the supercooled liquid water is very important in the cloud microphysical process, since the Goddard microphysical scheme allows for the coexistence of cloud water and cloud ice above the freezing level.

Fourthly, as stated before, two kinds of microphysical processes related to the cloud water are examined in the experiments C1 and C2. As a result, according to the snowfall simulation, the experiments C1 and B1 are in one group, whereas the experiments C2 and CTL are in the other group. There is no cloud water in experiment B1, and there is no condensation of super-

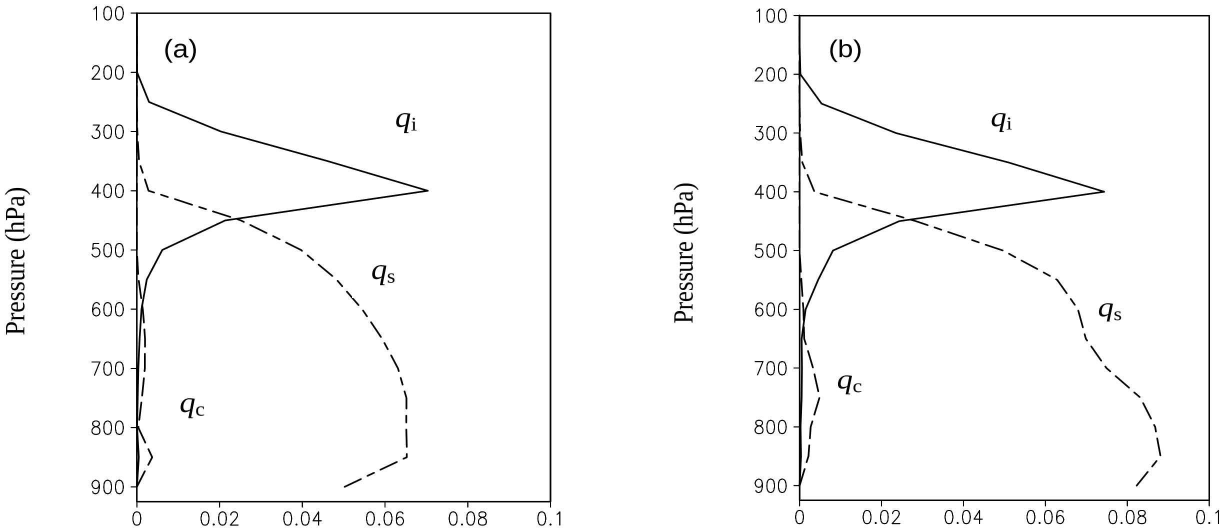

Fig. 6. Mean hydrometeors depicted as a function of height (a) at 12 hours, and (b) at 24 hours in the domain D03. The curves for the hydrometeors shown are cloud ice q_i (solid), cloud water q_c (dashed) and snow q_s (dot-dashed). The units in the figure are normalized with respect to the number of horizontal model grid points.

saturated vapor or evaporation of cloud water in experiment C1. This suggests that the other microphysical processes of cloud water have little impact on the simulated results and this will result in larger systematic errors if the microphysical processes of the condensation of supersaturated vapor and the evaporation of cloud water are neglected.

For the simulation of a moderate snowfall event in North China, some cloud physical processes in the Goddard microphysical parameterization can be stripped off, in which only the cloud water, cloud ice and snow are taken into account, and without the cumulus parameterization scheme. Moreover, the microphysical process related to the cloud water can be further simplified to include only the processes of the condensation of supersaturated vapor and the evaporation of cloud water. Because the cloud water does not possess a terminal velocity, it only causes a change of temperature, and in turn it alters the other dynamic fields and, thus, the precipitation. The result of experiment NN2, which is almost identical with that of the CTL, further supports such a viewpoint.

The Goddard microphysical parameterization scheme in the MM5 model is a single-moment three-category ice-phase scheme developed by Tao and Simpson (1993) and afterward modified by Braun and Tao (2000), in which six classes of water substances, including graupel or hail, are considered. Although the addition of graupel or hail allows an even more complete treatment of the precipitation processes, the results of the above twelve experiments tell us that the Goddard microphysical scheme can be stripped down for a moderate snow event. According to the cloud microphysical option of experiment NN2, there is only vapor, cloud water, cloud ice and snow in the scheme.

In order to examine the above preliminary conclusion, we conducted experiment HR, in which the domain D03 with a 6-km grid scale is included. The 6-km domain does not use parameterized convection because it was assumed that deep convection could be resolved reasonably well by the explicit microphysics at this scale (Liu et al, 1997). Figure 6 shows the domain averaged vertical distribution of the cloud water, cloud ice and snow, in which the maximum height of cloud ice is at 400 hPa, where there is a lot of snow and little supercooled liquid water. Significantly, although the surface temperature is less than 0°, there is cloud water in the air. This is because the Goddard scheme allows the coexistence of cloud water and cloud ice when the temperature is greater than $-40°$C and less than 0°C (Tao and Simpson, 1993; Tao et al., 1989).

Table 2 shows the description of all cloud microphysical processes in the Goddard scheme in the MM5 model and the vertically integrated cloud microphysics budgets during 0–12 hours and 12–24 hours in the domain D03. Most of the budgets for rain water and graupel do not occur or seldom occur in this snowfall event in North China. At 12 hours and 24 hours, the vertically integrated mass-weighted mixing ratios of rain water and graupel are zero, and the vertically integrated mass-weighted mixing ratios of cloud water are one order of magnitude smaller than those of cloud ice (Fig. 6). The total hydrometeors (especially cloud water) may be advected through the domain D03 because the lateral boundary of domain D03 is a nested boundary. The depositional growth of cloud ice $P_{\rm dep}$

Table 2. List of cloud microphysical processes in the Goddard microphysical parameterization scheme (after Tao and Simpson, 1993) and their vertically integrated budgets averaged over 0–12 hours and 12–24 hours. (Units: mm h^{-1}).

Notation	Description	0–12 hours	12–24 hours
$P_{\rm cnd}(>0)$	Condensation of supersaturated vapor	3.142	2.120
$P_{\rm cnd}(<0)$	Evaporation of sub-saturated vapor	−0.959	−0.495
$P_{\rm dep}(>0)$	Deposition of cloud ice	3.143	2.521
$P_{\rm dep}(<0)$	Sublimation of cloud ice	−2.057	−1.765
$P_{\rm ern}$	Evaporation of rain	0.000	0.000
$P_{\rm gaci}$	Accretion of cloud ice by graupel	0.000	0.000
$P_{\rm gacr}$	Accretion of rain by graupel	0.0	0.0
$P_{\rm gacs}$	Accretion of snow by graupel	0.0	0.0
$P_{\rm gacw}$	Accretion of cloud water by graupel	0.000	0.000
$P_{\rm gfr}$	Freezing of rain to form graupel	0.000	0.000
$P_{\rm gmlt}$	Melting of graupel to form rain	0.0	0.0
$P_{\rm gsub}$	Sublimation of graupel	0.000	0.000
$P_{\rm iacr}$	Accretion of rain by cloud ice	0.000	0.000
$P_{\rm idw}$	Depositional growth of cloud ice at expense of cloud water	0.001	0.001
$P_{\rm ihom}$	Homogeneous freezing of cloud water to form cloud ice	0.000	0.000
$P_{\rm imlt}$	Melting of cloud ice to form cloud water	0.0	0.0
$P_{\rm int}$	Initiation of cloud ice	1.956	2.024
$P_{\rm racw}$	Accretion of cloud water by rain	0.000	0.000
$P_{\rm raci}$	Accretion of cloud ice by rain	0.000	0.000
$P_{\rm racs}$	Accretion of snow by rain	0.0	0.0
$P_{\rm raut}$	Autoconversion of cloud water to form rain	0.0	0.0
$P_{\rm saci}$	Accretion of cloud ice by snow	0.105	0.124
$P_{\rm sacr}$	Accretion of rain by snow	0.000	0.000
$P_{\rm sacw}$	Accretion of cloud water by snow	1.423	0.973
$P_{\rm saut}$	Autoconversion of cloud ice to form snow	0.0	0.0
$P_{\rm sdep}$	Deposition growth of snow	2.397	1.497
$P_{\rm sfi}$	Bergeron process of cloud ice to form snow	4.185	3.488
$P_{\rm sfw}$	Bergeron process of cloud water to form snow	0.016	0.008
$P_{\rm smlt}$	Melting of snow to form rain	0	0
$P_{\rm ssub}$	Sublimation of snow	0	0
P	Rate of snowfall	0.262	0.202

becomes a dominant process to produce cloud ice (during 0–12 hours, $P_{\rm dep}$: 3.14 mm h^{-1}; during 12–24 hours, $P_{\rm dep}$: 2.52 mm h^{-1}). The Bergeron process of cloud ice $P_{\rm sfi}$ becomes a dominant process to produce snow (during 0–12 hours, $P_{\rm sfi}$: 4.18 mm h^{-1}; during 12–24 hours, $P_{\rm sfi}$: 3.49 mm h^{-1}). Although the supercooled liquid water is one order of magnitude smaller than that of cloud ice, the accretion of cloud water by snow $P_{\rm sacw}$ (during 0–12 hours, $P_{\rm sacw}$: 1.42 mm h^{-1}; during 12–24 hours, $\mathrm{P}_{\rm sacw}$: 0.97 mm h^{-1}) is as much as the deposition growth of snow $P_{\rm sdep}$ (during 0–12 hours, $P_{\rm sdep}$: 2.40 mm h^{-1}; during 12–24 hours, $P_{\rm sdep}$: 1.50 mm h^{-1}) and significantly larger than the accretion of cloud ice by snow $P_{\rm saci}$ (during 0–12 hours, $P_{\rm saci}$: 0.11 mm h^{-1}; during 12–24 hours, $P_{\rm saci}$: 0.12 mm h^{-1}). This shows that the supercooled liquid water plays a very important role in formation of snow.

If the budgets smaller than 0.01 mm h^{-1} are neglected, the following processes are left during 1–12 hours and 12–24 hours: the condensation (evaporation) of supersaturated (subsaturation) vapor $P_{\rm cnd}$, the depositional (sublimation) growth of cloud ice $P_{\rm dep}$, the initiation of cloud ice $P_{\rm int}$, the accretion of cloud ice by snow P_{saci}, the accretion of cloud water by snow $P_{\rm sacw}$, the deposition growth of snow $P_{\rm sdep}$, the Bergeron process of cloud ice to form snow $P_{\rm sfi}$. According to Fig. 6, the sources of vapor ($S_{\rm qv}$), cloud water ($S_{\rm qc}$), rain ($S_{\rm qr}$), cloud ice ($S_{\rm qi}$), snow ($S_{\rm qs}$), and graupel ($S_{\rm qg}$) in the Goddard microphysical scheme are individually shown by:

$$S_{\rm qv} = -P_{\rm cnd} - P_{\rm dep} - P_{\rm int} - P_{\rm sdep}$$

$$S_{\rm qc} = P_{\rm cnd} - P_{\rm sacw}$$

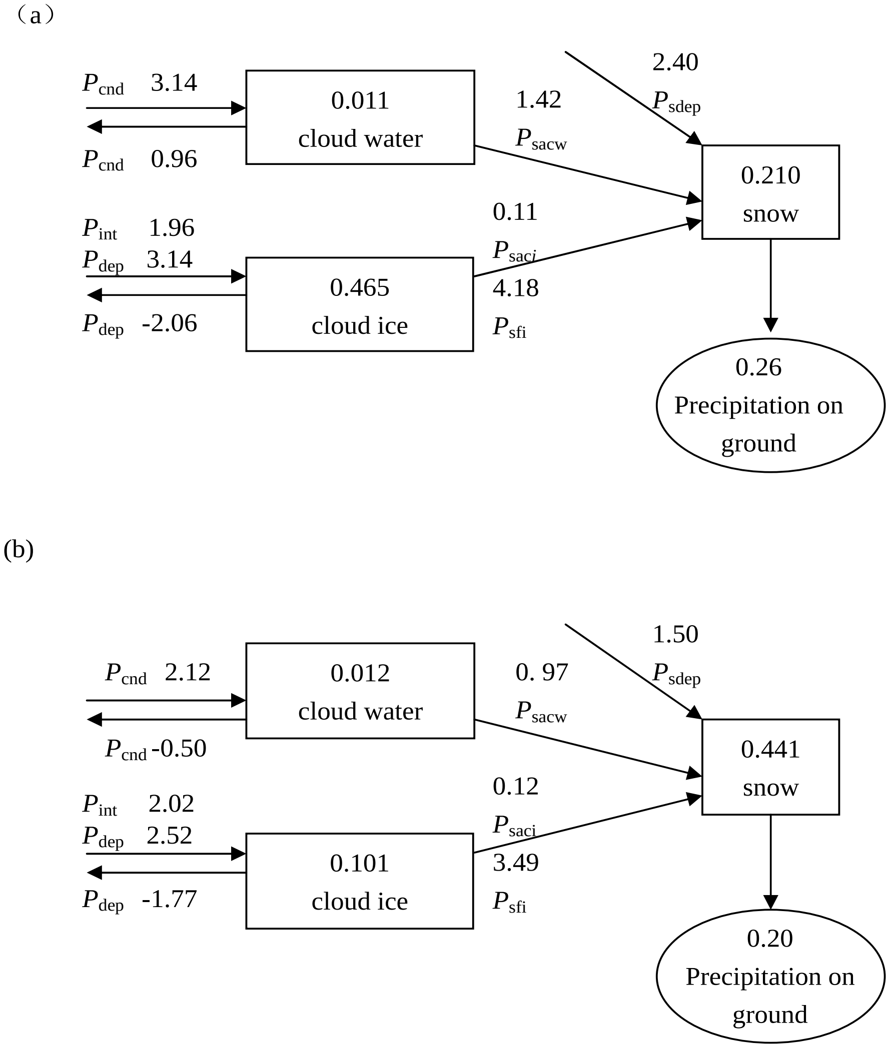

Fig. 7. Simulated cloud microphysics budgets averaged within (a) 0–12 hours, and (b) 12–24 hours in the domain D03. Units for cloud hydrometeors and conversions are mm and mm h^{-1}, respectively.

$$
\begin{aligned}
&S_{\rm qr}=0\\
&S_{\rm qi}=P_{\rm int}+P_{\rm dep}-P_{\rm saci}-P_{\rm sfi}\\
&S_{\rm qs}=P_{\rm sdep}+P_{\rm sacw}+P_{\rm saci}+P_{\rm sfi}\\
&S_{\rm qg}=0\,.
\end{aligned}
$$

4. Summary

Thirteen experiments were conducted to simulate a moderate snowfall event in North China. The results show that such a moderate snowfall event can be adequately simulated with a simplified Goddard cloud microphysical parameterization scheme and without the cumulus parameterization scheme. In the microphysical process of the moderate snowfall event, only the cloud water, cloud ice, and snow are taken into account, and the cloud water participates only in the processes of the condensation of supersaturated vapor and the evaporation of cloud water. The analysis of the cloud microphysics budgets in the explicit experiment shows that (1) the condensation of supersaturated vapor causes the growth of cloud water, (2) the depositional growth of cloud ice and the initiation of cloud ice produces cloud ice, and (3) the accretion of cloud ice by snow, the accretion of cloud water by snow, the deposition growth of snow, and the Bergeron process of cloud ice enhances snow. The accretion of cloud water by snow and the deposition growth of snow are equally important in the development of snow.

It needs to be pointed out that some of the conclusions are from the simulation of one case and for a moderate snowfall event only. The results derived from this numerical study are preliminary and need to be generalized with additional case studies. These cases include different model resolutions, different synoptic situations, and interaction with other physical processes. So much work needs to be done to extend this study.

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