Article Chinese Science Bulletin

Atmospheric Science

March 2012 Vol.57 No.9: 1055–1061
doi: 10.1007/s11434-011-4934-9

Cloud-resolving model for weather modification in China

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Received September 30, 2011; accepted December 5, 2011; published online January 31, 2012

Weather modification is widely carried out in China. It is important to develop an operational model for weather modification to predict the microphysical features of cloud and precipitation and to help locate possible seeding areas. A two-moment microphysics scheme is developed using a quasi-implicit calculation method. The scheme predicts the evolution of mass as well as the number densities of the five hydrometeor types. Some microphysical processes are specified. The scheme is implemented with mesoscale models that have been run operationally for weather modification in China.

cloud microphysical model, double-moment, quasi-implicit, weather modification application

Citation: Lou X F, Shi Y Q, Sun J, et al. Cloud-resolving model for weather modification in China. Chin Sci Bull, 2012, 57: 1055–1061, doi: 10.1007/s11434-011-4934-9

Water is one of the most basic commodities for sustaining human life. Weather modification activities to increase the water supply have been conducted by a wide variety of groups, including water resource managers, hydroelectric power companies and farmers. Rain enhancement experiments have shown that seeding increases precipitation under favorable conditions [1,2].

Cloud models have been used in weather modification to formulate cloud-seeding hypotheses; i.e. assessments of the cloud-seeding potential or “seedability” of a given cloud or cloud type or collection of clouds in a geographical region [3–5]. Models have also been applied in operational decision making, project evaluation and examining seeding effects [6]. Increasingly sophisticated models allow quantitative estimations of the effects of seeding and the conditions that optimize such treatment. Explicit cloud models within mesoscale models have been greatly developed in the past decade. In the fifth-generation Penn State/NCAR mesoscale model (MM5), all microphysical schemes only forecast mixing ratios of water substances which is called single-moment scheme [7]. In the Weather Research and Forecasting (WRF) model, however, there are several double-moment schemes [8,9]. In the Milbrandi-Yau scheme, number concentrations are predicted for all six water/ice species (i.e. it is a double-moment scheme). The WDM6 scheme [10] includes prognostic equations for the cloud water and the number concentration of cloud condensation nuclei, which allows the investigation of the aerosol effects on cloud properties and the precipitation process.

In China, weather modification has been carried out since 1958 to help relieve drought and suppress hail disasters. By 2007, China was conducting weather modification using artillery shells and rockets containing seeding agents in more than 30 provinces and using aircraft spraying seeding agents in 24 provinces [11].

Accurate forecasting and operational running have become increasingly important in weather modification in China. Models for weather modification are interesting in terms of both the macroscale and microscale features of cloud and precipitation. Therefore, a model of weather modification should not only forecast the mixing ratios of water substances but also forecast the number concentrations of particles. The prognostic variables of the number concentration are more important in some microphysical

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*Corresponding author (email: louxf@cams.cma.gov.cn) processes in which the mass contents are less sensitive than the number concentrations. For example, ice nucleation and multiplication have negligible effects on the ice mass content but increase the ice particle number concentration significantly. Additionally, the freezing of raindrops through the collection of ice particles depends mainly on the ice particle number concentration and not the mass content. It is widely accepted that the number concentrations of ice, rain embryos and hail embryos considerably affect the precipitation efficiency according to Bergeron theory, and that artificial increases in the number concentrations of ice and large cloud droplets is the basis of weather modification. Therefore, a cloud scheme that can be used in weather modification should describe microphysical processes and forecast the number concentrations and mass contents of water substances reasonably.

A physical variable of a cloud, such as the water content or number concentration of hydrometeors, is always positive. However, the microphysical source (sink) terms that are involved in the calculation of a cloud model vary greatly in different conditions. If the sink terms are large and the time step is too long, then the calculated cloud physical variables can be negative, which is unreasonable and can fail the calculation. In this paper, a quasi-implicit calculation scheme is developed to deal with this problem.

A two-moment scheme that propagates the number concentrations and mass contents of various hydrometeor particles is developed in which several microphysical processes are treated uniquely, such as the autoconversion of cloud to rain, the nucleation of ice, and the freezing of raindrops to graupel particles. Furthermore, a quasi-implicit approach that considers the feedback of temperature, water vapor and saturated specific humidity is designed. Additionally, the parameter number for the particle size distribution is not constant, which agrees with observations that the number varies widely and may suddenly change during a particular rainfall event [12]. This scheme is coupled with mesoscale models and is used to forecast seedability for weather modification in China.

1 Description of the new microphysics scheme

A two-moment bulk microphysics scheme has been developed [13]. In this scheme, based on phases and dimensions, water substances are divided into six categories (Table 1): water vapor, cloud droplets, rainwater, ice, snow and graupel.

Each category of water substance is assumed to have a size distribution of the form

$$N(D) = N_0 D^{\alpha} \exp(-\lambda D), \qquad (1)$$

where $N(D)\mathrm{d}D$ is the number of particles in the diameter range $\mathrm{d}D$ centered on D, and α, N_0 and λ are three spectrum parameters. α values are listed in Table 1. The Khrigian-Mazin distribution is assumed for cloud droplets ($\alpha = 2$), and the Marshall-Palmer distribution is taken for raindrops and graupel ($\alpha = 0$). Based on the observation results of Mason [14], for the size distributions of ice and snow, α is taken to be 1.

The 11 cloud variables predicted are the mass contents of water vapor Q_v, cloud droplets Q_c, rainwater Q_r, ice Q_i, snow Q_s and graupel Q_g, and the number concentrations of ice N_i, snow N_s, rainwater N_r and graupel N_g. In addition, to describe the autoconversion of cloud water to rain water, a relatively broad cloud droplet size distribution function F_c is used. To preserve the positivity, conservation and stability of the water substance, a quasi-implicit calculation framework was developed. A specific calculation sequence is used to calculate the cloud physical variables.

A total of 31 microphysical processes are considered, including autoconversion, collection, condensation and evaporation, freezing and melting, sublimation and deposition. All microphysical processes of mass contents are denoted by three letters. The first capital letter represents the transformation process, and the second and third lowercase letters represent the dissipation and production phases of the water substance respectively. Transformation processes are collection (C), autoconversion (A), melting (M), freezing (F), nucleation and multiplication (P), and deposition (sublimation) and condensation (evaporation) (S). The three letters with an additional letter N in front are used to express the changing rate of the number concentration for the given process. For example, Cir represents the mass conversion rate for the collection of ice by rain, and NCir represents the number changing rate for the collection of ice by rain. The 31 microphysical processes simulated by the

Table 1 Water substance categories and their α values included in the quasi-implicit two-moment scheme

Category	Definition	Diameter (cm)	Mixing ratio (Q) and number concentration (N)	α value
Water vapor	Gas	–	Q_v	–
Cloud water	Liquid, D<0.02 cm	1.2×10^{-4}–0.02	Q_c (F_c)	2
Rain water	Liquid, D>0.02 cm	0.02–0.6	Q_r, N_r	0
Ice	Ice crystals, D<0.03 cm	3.0×10^{-4}–0.03	Q_i, N_i	1
Snow	Ice crystals, D>0.03 cm	0.03–2.0	Q_s, N_s	1
Graupel	Solid particles, consists mainly of rimed droplets	0.04–0.5	Q_g, N_g	0

scheme are autoconversion of cloud-rain, cloud-graupel, cloud-ice, ice-snow, snow-graupel (Acr, Acg, Aci, Ais, Asg); collection of cloud droplets by rain, graupel and snow (Ccr, Ccg, Ccs); collection of ice by rain, graupel, snow and ice (Cir, Cig, Cis, NCii); collection of rain by graupel, snow, ice and rain (Crg, Crs, Cri, NCrr); collection of snow by rain, graupel and snow (Csr, Csg, NCss); ice nucleation and multiplication (Pvi, Pci); melting of ice, snow and graupel (Mic, Msc, Msr, Mgr); freezing of rain to graupel (Frg); deposition (sublimation) of ice, snow and graupel (Svi, Svs, Svg); condensation (evaporation) of cloud and rain (Svc, Svr) (Table 2).

Several microphysical processes in the new scheme are treated uniquely. The number concentrations of raindrops are predicted following Hu et al. [15], which eliminates the need to prescribe the truncated values of spectra as a function of the respective precipitation rate or constant. On the basis of the numerical simulation results of Berry [16], a variable indicating the broadness of the droplet size distribution (F_c) is predicted. If F_c is larger than 1, a number of rain embryos are converted from the growing cloud droplet population. The number concentration of activated ice nuclei is taken as a function of temperature following Fletcher [17], and the nucleation rate of ice is taken as a function of the change rate of temperature and the vapor supersaturation. The minimum diameter of cloud droplets (24 μm) is set as that that can be collected and form secondary ice. The freezing of raindrops to graupel particles (Mrg) is calculated from the possibility function of freezing (Pfrg), considering the change rate of T, the number change rate of rain drops and the volume change rate of rain drops. Additionally, a quasi- implicit calculation method is established for all microphysical processes.

Table 2 The 13 microphysical processes[a)]

Categories	Microphysical processes
Collection of cloud water	Ccr, Ccg, Ccs
Collection of ice	Cir, Cis, Cig, NCii
Collection of rain drop	Cri, Crs, Crg, NCrr
Collection of snow	Csr, Csg, NCss
Deposition	Svi, Svs, Svg
Condensation (evaporation)	Svc, Svr
Autoconversion	Acr, Aci, Acg, Ais, Asg
Nucleation and multiplication	Pvi, Pci
Freezing and melting	Frg, Mic, Msc, Msr, Mgr

a) The 31 microphysical processes in the scheme. The leading letter of a microphysical process is the abbreviation for the name of the process; the second and third letters stand for the depletion and production phases of the water substance, respectively. These three letters with an additional letter N in front are used to express the change rate of the number concentration. NCii, NCrr and NCss are processes only having number concentrations.

2 Quasi-implicit calculation method

To maintain the positive-definiteness, conservation and stability of the water substances, a quasi-implicit calculating framework is developed.

A microphysical variable at the time step t+1 is calculated as

$$A_n^{t+1} = A_n^t + (\mathrm{ADV}_n + \mathrm{DIF}_n)Dt + \sum_{ij} F_{ijn} \cdot Dt - \sum_{ik} F_{ink} \cdot Dt + \mathrm{FAL}_n \cdot Dt, \tag{2}$$

where ADV_n, DIF_n and FAL_n are the advection, eddy mixing and fallout terms of A_n, respectively. In eq. (2), F_{ijn} is the source term of the cloud variable n and the sink term of variable j due to cloud microphysical process F_i. If $\sum_{ik} F_{ink} \cdot Dt$ is very large, the value of A_n^{t+1} may be negative.

A cloud value's change rates of sink terms have a positive correlation with the consumed quantity, and values of the sink term can be written as

$$F_{ijk} = H_{ijk} \cdot A_j, \tag{3}$$

where H_{ijk} is the relative depletion rate of A_j with a unit of s^{-1}.

The quasi-implicit difference scheme is proposed as

$$A_n^{t+1} = A_n^t + (\mathrm{ADV}_n^t + \mathrm{DIF}_n^t + \mathrm{FAL}_n^t - \sum_{ik} H_{ink}^t \cdot A_n^{t+1} + \sum_{ij} H_{ijn}^t \cdot A_j^{t+1}) \cdot Dt. \tag{4}$$

A specific calculation sequence is used to calculate the cloud physical variables. First, variables with more sink terms and less source terms are calculated, and then those with less sink terms and more source terms are calculated, which simplifies the calculation. According to eq. (4),

$$A_n^{**} = (A_n^* + \sum_{ij} H_{ijn}^t \cdot A_j^{t+1} \cdot Dt) / (1 + \sum_{ik} H_{ink}^t \cdot Dt), \tag{5}$$

where

$$A_n^* = A_n^t + (\mathrm{ADV}_n^t + \mathrm{DIF}_n^t) \cdot Dt. \tag{6}$$

The calculation sequence in a warm region ($T \geqslant 0$°C) is ice, cloud water, snow, graupel and rain drops, because ice and cloud water are collected by larger particles of snow and graupel, and then snow and graupel melt to rain. In a cold region ($T < 0$°C), the order is ice, cloud water, snow, rain drop and graupel, because ice and cloud water are collected by larger particles of snow and graupel as in the warm region, and rain drops freeze to graupel.

After calculation of the above microphysical processes of collection, freezing and melting, the new temperature and mass contents and number concentrations of water substances are obtained. The quasi-implicit condensation (deposition) approach is used, considering the feedback for temperature, water vapor and saturated specific humidity. Water vapor and temperature are calculated as

$$Q_v^* = Q_v^t + [\mathrm{ADV}^t(Q_v) + \mathrm{DIF}^t(Q_v)] \cdot Dt, \tag{7}$$

$$T^{**} = T^t + [\mathrm{ADV}^t(T) + \mathrm{DIF}^t(T)] \cdot Dt + \frac{L_f}{C_p}(\sum_i F_{ils} - \sum_i F_{isl}) \cdot Dt, \tag{8}$$

where F_{ils} and F_{isl} are the change rates for liquid water freezing to solid water and solid water melting to liquid water, respectively. The saturation water and ice specific humidity are recalculated with T^{**}:

$$Q_{sw}^{**} = Q_{sw}(P, T^{**}), \quad Q_{si}^{**} = Q_{si}(P, T^{**}). \tag{9}$$

Using these values, the quasi-implicit condensation (deposition) approach is employed to avoid iteration and allow a comparatively long time step.

Employing this quasi-implicit method, in addition to having the advantages of handling microphysical processes, the scheme is able to simulate the mass contents and number concentrations of water substances for weather modification.

3 Cycle running for weather modification

The model is implemented for the MM5 and Global/ Regional Assimilation and PrEdiction System (GRAPES) [18,19]; the implementations are named MM5-CAMS and GRAPES-CAMS respectively. Four new variables are added to these two models: the number concentrations of snow (N_s), rain water (N_r) and graupel (N_g), and the broadness of the cloud droplet spectrum (F_c) [20]. MM5-CAMS and GRAPES-CAMS were put into operation in 2007 at the Chinese Academy of Meteorological Sciences. The T213 field is used as their initial input data. MM5-CAMS has two nested domains with 5-km and 15-km horizontal resolutions while GRAPES-CAMS has one domain with 15-km horizontal to provide analyses/forecasts (0–36 h).

MM5-CAMS and GRAPES-CAMS model results have been compared with satellite data and ground observation data, such as the rainfall intensity, surface temperature, and the satellite FY-2 retrieved cloud top and optical thickness, and it was confirmed that the two models employing the new scheme run stably and produce reasonable results [21,22].

The numerical results obtained using the two models have been used in seedability analysis and forecasting to modify weather in China. The better simulation of precipitation with the two models compared with a forecast issued by the National Meteorological Centre (NMC) has been used to analyze and forecast seedability. The seedability forecast considers the rainfall amount and rainfall areas in the NMC forecast.

Applications of the model results in weather modification include rain enhancement in the case of severe drought such as that in southwestern China in 2010, which threatened the lives of people and animals; rain and cloud suppression for special social activities, such as the opening ceremony of the Beijing Olympic Games in 2008, Asian Games in 2010, and the 60th National Anniversary in 2009; and forecasts in fighting forest fires. The models were also used to forecast freezing rain in the winters of 2008 and 2009.

Horizontal distributions of vertically integrated supercooled liquid water for southwestern China on March 28th, 2010 during a severe drought are given in Figure 1. Figure 2 presents the vertical cross sections of water substances and temperature. The model output of supercooled cloud water, and its height, along with distributions of other water substances are used to help allocate possible seeding areas for weather modification.

4 Hindcast experiments of model simulations

A concentrated effort to conduct a hindcast experiment of the model results was made from April 1 to May 10, 2010. The model output the columnar supercooled liquid water, mass content and number concentration of water substances along with other physical fields to help analyze seeding ability and locate areas of possible seedability. Seedability has four factors as listed in Table 3: precipitation intensity (>0.1 mm/h), cloud water content (>0.01 g/kg), temperature

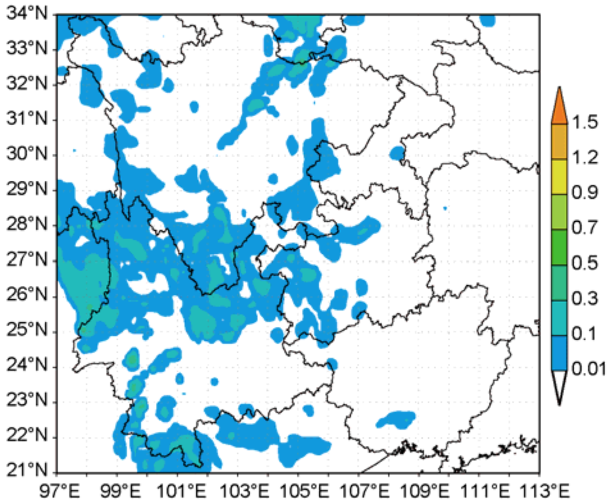

Figure 1 Horizontal distribution of vertically integrated supercooled liquid water (g/kg) in southwestern China on March 28, 2010 during a severe drought.

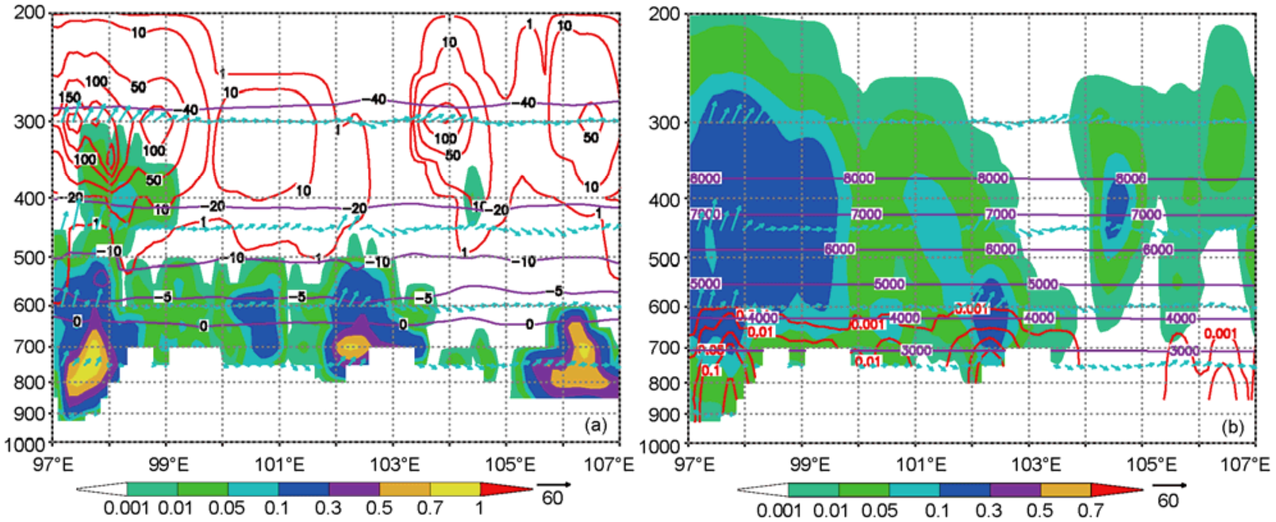

Figure 2 Vertical sections of cloud water, ice, snow and graupel, and rainwater substances along 26.0°N at 09:00 on March 28, 2010. (a) The ice particle number concentration (L^{-1}) is shown with red lines and the cloud water (g/kg) with color shading. The purple lines indicate temperatures of 0°C, –5°C, –10°C, –20°C, and –40°C. (b) The rain water content (g/kg) is shown with brown lines and the snow and graupel content (g/kg) with colored shading. The purple lines indicate heights from 3000 to 8000 m at 1000 m intervals. The white button blank under 700 hPa is terrain of the Yunnan-Kweichow Plateau in southwestern China.

(0–20°C), and ice particle number concentration (<100/L). Seedable locations are marked manually with circles or ellipses according to model simulations of these four factors.

Field operations are carried out when there is seedability according to the analysis of observations of the cloud condition, such as satellite data, radar data, surface precipitation, and sounding data. Therefore, the forecast of model seedability is verified in the field.

The seedability locations are divided into four severe-drought provinces, namely Yunnan, Sichuan, Guizhou and Guangxi, because rain-enhancement field operations are managed by provinces and field operations are reported to and accumulated by all provinces. Each day in each province is referred to a case in this research, and there are therefore 160 cases in 40 days for the four provinces. Model-forecasted seedability and field operations are listed in Table 4. It is seen that the model forecasts seedability well. There are a total of 99 cases of a forecast indicating seedability and field operations having been undertaken in the four provinces, and there are 30 cases of the model forecasting no seedability and no field operations having been undertaken, indicating correct model forecasting of seedability in both scenarios.

The model makes incorrect forecasts in some cases; i.e. either the model incorrectly forecasts no possibility of seeding but there were field operations (i.e. missed opportunities) or it gives a false alarm. There are nine cases of missed opportunities, accounting for 5.6% of cases. There are 22 cases of the model forecasting seedability but no field operations being undertaken, giving a false-alarm rate of 13.7%. The model also slightly over-forecasts precipitation. Among the 160 cases, the model forecasts 130 rainfall cases, while 122 rainfall cases are observed.

Table 3 Physical parameters affecting seedability

Seedability	Precipitation intensity (mm/h)	Q_c (g/kg)	Temperature (°C)	Ni (L^{-1})
Good	>0.1	>0.01	0 to –20	20–100
Better	>0.1	>0.01	0 to –20	<20

Table 4 Cases of model forecasting of seedability and field operations in Yunnan, Sichuan, Guizhou, Guangxi from April 1 to May 10, 2010 in southwestern China

	Seedable cases	None seedable cases	Rainfall cases
Model simulation	121	39	130
Field operation or observation	99	30	122

The distributions of the model-simulated supercooled water and the forecast of seedable areas and field operation activity in southwestern China on April 6, 2010 are shown in Figure 3. From the hourly simulations of supercooled cloud water, the model simulations of precipitation, ice particle number concentration and temperature, and the NWC prediction of rainfall, three seedable regions are predicted for that day, which are manually marked with ellipses. Field operation activities on that day comprised the use of rockets, anti-gun and aircraft. On that day, 32 rockets and 50 anti-gun shells were launched, and seeding agents of AgI were introduced into clouds during five flights. The timing of the launches of all rockets and anti-gun shells was staggered with the timing of flights as dictated by air traffic control. The forecast seedable regions cover most locations of field activity.

The comparisons clearly show that MM5-CAMS and GRAPES-CAMS well predict seedability. This validation

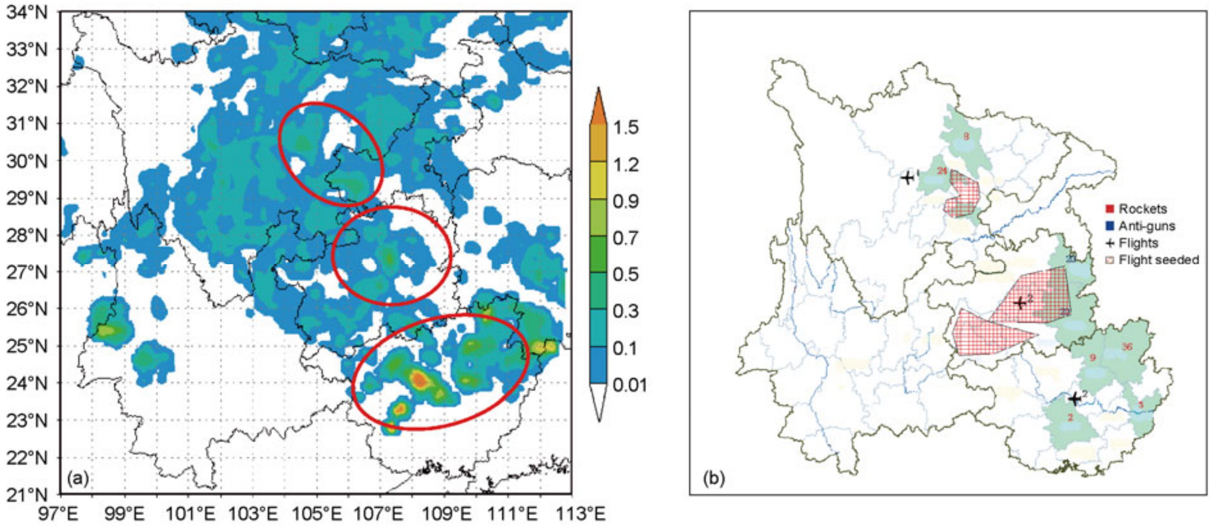

Figure 3 Distributions of model-forecasted supercooled water and seedability regions and field operation activity in southwestern China. (a) Model forecast made for the period from 2010-04-06 08:00 to 2010-04-07 08:00; red circles indicate seedability regions. (b) Field operations observed from 2010-04-06 08:00 to 2010-04-07 08:00. Red numbers: rockets; blue numbers: anti-gun shells; black numbers: flights; red hatching: flight-seeded areas; green shaded: rocket- and shell-seeded areas.

indicates that MM5-CAMS and GRAPES-CAMS can be used for weather modification in China. The hourly model outputs are published on a website for weather modification persons to arrange field operations, such as the design of flight paths and application for airspace, and the location of rockets and anti-gun sites and preparation of shells.

5 Conclusions

A two-moment quasi-implicit cloud scheme having 11 cloud variables was developed. The scheme considers the water contents and number concentrations of cloud droplets, ice crystals, snow crystals, rain drops and graupel particles. Several microphysical processes in the new scheme are specified, and a quasi-implicit approach is employed. The scheme does not require iteration and can be used in simulation with a comparatively long time step.

The model was implemented with MM5 and GRAPES after new variables were added, namely the broadness of the cloud droplet spectrum (F_c) and number concentrations of water substances. These two models have been run operationally since 2007, and have been used in analyses of weather forecasts and rain enhancement seedability to conduct weather modification in China. Validation indicates that MM5-CAMS and GRAPES-CAMS can be used for weather modification in China. Hourly model outputs are published on a website to assist field operations in weather modification.

The authors thank the Weather Modification Forecast and Data Group of the Weather Modification Center. This work was supported by the National Basic Research Program of China (2011CB403404), the Special Foundation of Chinese Academy of Meteorological Sciences (2011Z005), the National Natural Science Foundation of China (41075100 and 40805003) and the Social Commonweal Research Project (2004DIB3J116 and GYHY201106031).

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