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Advances in Cloud Physics and Weather Modification in China

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ABSTRACT

The capabilities of cloud-resolving numerical models, observational instruments and cloud seeding have improved greatly over recent years in China. The subject of this review focuses on the main progresses made in China in the areas of cloud modeling, field observations, aerosol–cloud interactions, the effects of urbanization on cloud and precipitation, and weather modification.

Well-equipped aircraft and ground-based advanced Doppler and polarized radars have been rapidly applied in cloud-seeding operations. The combined use of modern techniques such as the Global Positioning System, remote sensing, and Geographical Information Systems has greatly decreased the blindness and uncertainties in weather-modification activities. Weather-modification models based on state-of-the-art cloud-resolving models are operationally run at the National Weather Modification Centre in China for guiding weather-modification programs.

Despite important progress having been made, many critical issues or challenges remain to be solved, or require stronger scientific evidence and support, such as the chain of physical events involved in the effects induced by cloud seeding. Current important progresses in measurements and seeding techniques provide the opportunity and possibility to reduce these deficiencies. Long-term scientific projects aimed at reducing these key uncertainties are extremely urgent and important for weather-modification activities in China.

Key words: advances, cloud physics, weather modification, China

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1. Introduction

Cloud physics is the study of the physical processes that lead to the formation, growth and precipitation of clouds, and is critical in our understanding of precipitation formation and climate change, as well as improving weather forecasts and the scientific basis of weather modification activities.

The state of cloud physics and weather modification has been discussed well from the perspective of laboratory, modeling and field experimental studies (e.g., Cotton, 1986; Rogers and DeMott, 1991; Orville, 1996; Pruppacher and Klett, 1997; Bruintjes, 1999; Silverman, 2001; National Research Council, 2003; List, 2004; Garstang et al., 2005). The major progresses in cloud physics and weather modification in China have also been briefly reviewed (Huang et al., 2003; Fang et al., 2003; Guo et al., 2003; Zheng et al., 2003; Mao and Zheng, 2006; Yao, 2006; Ma et al., 2007; Guo and Zheng, 2009; Guo et al., 2013).

Cloud-resolving numerical models are of great importance in cloud physics and weather modification studies (National Research Council, 2003; List, 2004; Garstang et al., 2005). Orville (1996) reviewed cloud modeling in weather modification, and showed that it was not until the late 1950s that modeling began to take shape (Saunders, 1957; Malkus and Witt, 1959), and theoretical developments in cloud seeding have come about mainly through the use of cloud models. China started to develop cloud models in the early 1960s (Gu, 1962, Xu and Gu, 1963), but then unfortunately almost stopped for about ten years from the end of the 1960s to the end of the 1970s. However, intensive and substantial field experiments on hail suppression were conducted during this period (Huang and Wang, 1980).

The reactivation of cloud modeling studies in the 1980s primarily came about to meet the needs of hail suppression activities. A better understanding of hail formation processes such as hail embryo formation, transport and further growth is essential to conduct effective hail suppression operations. For this purpose, hail-cloud models in 1D, 2D and 3D with one-moment and two-moment microphysical schemes have been constructed and applied in studies of hail formation and growth processes in convective clouds (Mao et al., 1982; Xu and Wang, 1985, 1988; Hu and He, 1987), almost in parallel to those studies conducted by researchers outside China in the late 1970s and early 1980s (e.g., Orville and Kopp, 1977; Weisman and Klemp, 1982, 1984). Most hail-cloud

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models use elastic dynamics approximations, simplified microphysics and ideal initiations. Very few models included cloud seeding processes, as performed by Orville and Chen (1982), until the 1990s, although the effect of cloud condensation nuclei (CCN) on cloud formation has been investigated in a few studies (e.g., Xu et al., 1983).

Important progress in the development and application of cloud models was made in and after the 1990s, as more powerful computing resources became available. Cloud models with sophisticated dynamics and detailed ice microphysics have been developed to study hail formation process in China (Kong et al., 1990, Kong, 1991, Kong et al., 1991; Guo, 1997; Hong, 1998).

The AgI-seeding process was developed in a 2D version of a cloud model (Huang and Xu, 1994), which was quite similar to the work of Orville and Chen (1982). The nucleation processes of the seeding agents of AgI and liquid-CO_2 were developed in the hail-bin model to compare dynamic and microphysical effects induced by two seeding agents (Guo et al., 2003; 2006a) in an attempt to obtain optimal cloud seeding methods (Guo et al., 2007). However, most cloud models are initialized by a single sounding dataset, which provides a homogeneous meteorological field and cannot reflect realistic cloud formation and evolution. To solve this problem, studies on cloud models initialized with output from the Fifth-Generation Penn State/NCAR (National Center for Atmospheric Research) Mesoscale Model (MM5) were conducted (e.g., Guo and Fu, 2003; Kang et al., 2004a, 2004b).

With the development of mesoscale cloud-resolving models [e.g., MM5, the Weather Research and Forecasting (WRF) model, and The Global and Regional Assimilation and Prediction System (GRAPES)] and powerful computing ability, more sophisticated and detailed dynamics and microphysics are available in these models. The AgI-seeding process was first developed in WRF-based cloud-resolving models in China, because the seeding effect on cloud and precipitation can be more realistically tested and evaluated based on this model (Fang et al., 2009). Also, the application of these cloud-resolving models has become common in a variety of topics, such as the formation mechanism of severe storms, aerosol–cloud interactions, and the impact of cloud merging, ice processes, and topography on precipitation (Guo et al., 2006b; Fu et al., 2011; Fu and Guo, 2012; Guo et al., 2013), as well as guiding operational cloud-seeding activities (Lou et al., 2012). The studies related to these issues in China are also reported in this review paper.

China has been one of the most active countries in operational weather modification programs. The first cloud-seeding experiments were conducted in both northern and western China in 1958 (Cheng, 1959). Meteorological disasters account for over 70% of natural damage in China, in which severe drought, flood, hailstorms and fog are more frequent. The severe situation of weather hazards and water stress has motivated the rapid development of weather modification activities in terms of rain enhancement and hail suppression in China.

Important progress in technologies and methodologies of weather modification has been made in the past several decades, particularly in the development and application of advanced observational tools in operational weather modification activities. An important achievement is that modern technologies such as the Global Positioning System (GPS), remote sensing, and Geographical Information Systems (GISs) have been effectively combined and incorporated into decision-making systems of weather modification activities, through which the displaying, monitoring and tracking of cloud seeding are available. The different types of radars, satellites, airborne measurements and operational mesoscale models are widely used in guiding and evaluating cloud seeding.

This paper reviews the current state of cloud physics and weather modification, paying particular attention to the modeling, technological and methodological developments in the last several decades in China. In doing so, the major uncertainties or challenges that limit advances in research and operational weather modification are identified, and recommendations for future avenues of research are provided to help reduce these critical issues. Following this introduction, section two addresses the progress made in cloud physics and weather modification in China, including cloud modeling and simulations, field investigations of aerosol, CCN and cloud properties, climatology and variations in cloud water retrieved from satellite data, as well as weather modification and its scientific basis in China. Conclusions and further discussion are presented in the final section.

2. Progress in cloud physics and weather modification

The complicated formation processes of cloud systems lead to an incomplete understanding of the precise mechanism of how a cloud forms and grows. In addition, different cloud formation mechanisms in different climatic and geographical regions increase the difficulty of cloud formation studies. Over several decades, studies of cloud physics in China have seen increasing interest in a wide variety of topics covering cloud modeling and field experiments, relationships between cloud physics and precipitation, hail, lightning, and aerosol–cloud–radiation interactions, due to the increasing demands of weather forecasting, climate change and weather modification activities (Ma et al., 2007; Guo and Zheng, 2009).

2.1. *Clouds and precipitation modeling and simulations*

2.1.1. *Hail-cloud modeling and simulations*

As a common form of meteorological disaster, hail clouds cause great damage to crops and property every year in many areas across China. In order to understand hail formation processes and search for effective hail suppression technologies, Chinese scientists have for decades made great efforts to understand hail formation mechanisms based on hail-cloud modeling studies (Huang et al., 2000, 2003; Zheng et al., 2003; Guo and Fu, 2003; Fang et al., 2003). Cloud models have been developed and applied in many aspects.

2.1.1.1. Understanding the microphysics and dynamics of hail clouds

A large amount of published papers can be classified into this category (Xu and Xia, 1964; Mao et al., 1982; Xu, 1985; Xu and Wang, 1985; Hu and He, 1987; Xu and Wang, 1988; Kong et al., 1990, Kong, 1991; Kong et al., 1991; Guo, 1997; Hong, 1998; Lin et al., 2000; Guo et al., 2000, 2001a, b; Guo and Huang, 2002; Hong et al., 2002; Qi et al., 2002a, b; Xiao et al., 2002; Wang et al., 2002; Fang et al., 2002; Kang et al., 2004a, b). Cloud models have developed from 1D to 2D and 3D with one-moment, two-moment and bin microphysical schemes. Kong et al. (1990, 1991) developed a time-dependent, non-hydrostatic, fully-elastic 3D cloud model with a one-moment scheme of hail microphysics and investigated the effect of low-level wind shear and cold water surfaces on hailstorm development and movement. The size distribution of hailstones is usually assumed to be distributed by an inverse exponential size distribution and their growth rates are based on mass weighted mean terminal velocities in one- and two-moment schemes. These assumptions may cause large errors, particularly in the size ranges varying significantly over the spectrum. Therefore, a cloud model with hail-bin microphysics was developed and applied in hail formation research (Guo, 1997; Guo et al., 2000, 2001a, b; Guo and Huang, 2002). The hail growth via the recirculation process in a multicellular hailstorm can be simulated well.

Hail forecasting and warning systems have also been tested (Mao et al., 1982; Xiao et al., 2002) as previously carried out by Cotton and Boulanger (1975). In addition, the hail-cloud models used in this period were usually initialized with single sounding datasets and the convection was initiated with an idealized thermal bubble, which cannot reflect the formation and evolution processes of real hailstorms, thus limiting the application in hail suppression activities. In order to predict the location, time and amount of hailfall and provide more realistic information on hail clouds, cloud models initialized with MM5 have been attempted (Guo and Fu, 2003; Kang et al., 2004a, b).

2.1.1.2. Understanding cloud seeding process

Cloud seeding processes, similar to those in the work of Orville and Chen (1982), have been developed in cloud models and applied in evaluating and understanding AgI-seeding effects (Hong, 1999; Li et al., 2003; Zhou et al., 2003; Guo et al., 2006a; Xiao et al., 2006), testing hypotheses such as the role of the accumulation zone of supercooled water in hail formation, as proposed by Sulakvelidze et al. (1967) in the 1960s It has been found that there is an obvious accumulation zone of supercooled water, which plays an important role in forming hailstones in convective clouds in western China (Zhou et al., 2001; Hu et al., 2003), and the so-called beneficial competition mechanism has been described (Xu and Duan, 2001, 2002). Also, cloud models have been applied in optimizing seeding methods (e.g., Guo et al., 2007), leading to the finding that the seeding in the maximum updraft region or maximum supercooled water region can obtain the largest surface rainfall. The application of cloud models in weather modification is discussed in more detail in section 2.4.

2.1.1.3. Investigating severe wind-producing storms

Cloud models have also been used to better understand the formation mechanisms of severe winds (downbursts) produced by convective cloud systems. Cloud models with bin microphysics have been used to investigate the contribution of the various hydrometeor types on downdraft formation by calculating the equivalent cooling rates (Hjelmfelt et al., 1989; Guo et al., 1999a, b; Guo and Fu, 2003; Fu et al., 2003; Sun et al., 2004; Fu and Guo, 2007).

Time–height distributions of the simulated maximum downdrafts and hail/graupel and rainwater content indicate that downbursts are primarily produced by hail/graupel and rain loading in the upper layers, and then enhanced by hail/graupel melting and rain evaporation after the particles pass through the melting layers.

Severe surface winds could not be reasonably simulated and explained by negative buoyancy induced by loading and melting processes in a case simulated by Liu and Guo (2012a). Recent studies found that a descending rear-inflow jet, which was collocated with a mesovortex along the leading convective line, might cause severe surface winds (Trapp and Weisman, 2003; Atkins and Laurent, 2009). Houze et al. (1989) proposed the concept of convective momentum transport (CMT) in mesoscale convective systems (MCSs) to illustrate the accelerated flow, and how flow from the rear of the MCS can be accelerated via the pressure gradient force and transported downward.

The effects of the surface cold pool and CMT in the formation of severe surface winds on 3–4 June 2009 in China were investigated using the WRF model. The results indicated that there was a strong westerly jet belt with wind speed of > 30 m s^{-1} and 5 km thickness at levels of 11–16 km. The jet belt accelerated and descended while the squall line convective system occurred. The negative buoyancy due to the loading, melting and evaporation of cloud hydrometeors induced the downward momentum transport from the upper levels. The contributions to the formation of severe surface winds from downward momentum transport accounted for about 70%, while the surface cold pool accounted for about 30% (Liu and Guo, 2012a, b).

With the development of mesoscale cloud-resolving models (e.g., MM5, WRF, GRAPES), more detailed hail-cloud microphysics has become available. The application of these mesoscale models in cloud and precipitation formation studies, as well as in guiding cloud-seeding activities, has become increasingly common in China. The relevant progress in this regard is described in the following sections.

2.1.2. *Effects of ice microphysics and cloud-merging processes on precipitation formation in MCSs*

Various effects of cloud microphysics on the formation and evolution, as well as the precipitation, of MCSs have been described. The conclusions, however, are inconsistent, and even contrary to one another in some respects. When convective systems are simulated without ice microphysics, a reduced stratiform component can occur, as well as a faster propagation speed and a shorter life cycle, as compared to simulations with ice microphysics (e.g., Grabowski, 2003; Tao, 2007; Tao and Moncrieff, 2009). On the contrary, similar propagation speeds and life cycles of convective systems have also been obtained with and without ice microphysical simulations (e.g., Tao and Moncrieff, 2009).

Investigations on the precipitation difference between ice-free and ice runs have also been conducted, and based on the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE) bulk flux algorithm it has been found that precipitation increases in the ice run (e.g., Tao et al., 2003). The recently improved ice microphysical processes in the WRF model enable a more realistic representation of the formation of cloud ice in the cloud model (Hong and Lim, 2006). The effects of cloud microphysics on monsoon MCSs was investigated by Fu et al. (2011) based again on the cloud-resolving WRF model over the South China Sea Monsoon Experiment (SCSMEX) region. The sensitivity experiments with ice runs and ice-free runs showed that the ice run can produce less rain prior to and during the onset of the monsoon period. The reason is due to the different cloud microphysics having different responses to radiation processes. Therefore, the effect of ice microphysics on precipitation is determined through the radiation processes instead of the microphysics itself.

The role of cumulus merging processes in the formation of MCSs has been widely investigated in terms of the development and enhancement of the cloud echo area, mixed-phase microphysics, rainfall and cloud-to-ground lighting activities, as well as the possible application in weather modification (e.g., Rosenfeld and Woodley, 1993; Changnon et al., 1995; Czys et al., 1995). Previous numerical simulations, however, generally adopted idealized methods to initiate the convection, which could not objectively reflect the natural cloud-merging processes. Fu and Guo (2006, 2012) investigated the cumulus-merging processes in generating an MCS that occurred on 23 August 2001 in the Beijing region by using a cloud-resolving mesoscale model of MM5, and found that the formation of the MCS experienced multiscale merging processes from the single-cell scale to the cloud cluster-scale, and echo-cores merging within the MCS. The merger process can apparently alter cloud dynamical and microphysical properties through enhancing both low- and middle-level forcing. Also, lightning flash rates are enhanced by the production of more intense and deeper convective cells by the merger process, by which the more graupel-like ice particles especially are formed in clouds. Explosive convective development and a late peaking lightning flash rate can be found during the merger process.

Li et al. (2011, 2013) investigated the cloud structure and evolution of MCSs retrieved from the Microwave Imager (TMI) and Precipitation Radar (PR) of the Tropical Rainfall Measuring Mission (TRMM) and made comparisons with some pioneering studies based on soundings and models over the northern South China Sea. TRMM-retrieved rainfall amounts were generally consistent with those estimated from soundings and models. However, sounding- and PR-based estimates were relatively higher than TRMM-TMI-retrieved results. The WRF-based simulation underestimated the maximum rainfall rate by 27% compared to that derived from TRMM-PR, and underestimated mean rainfall by 10.4% and 12.5% compared to the TRMM-TMI and sounding estimates, respectively. In addition, apparent phase shifts among different retrievals existed.

2.1.3. *The effects of modification of urbanization and aerosols on cloud and precipitation*

Many observational and modeling studies outside China have indicated that rainfall patterns, amount and distribution in and downwind of cities can be modified (e.g., Bornstein and Lin, 2000; Shepherd et al., 2002; Rozoff et al., 2003). In China, abnormal precipitation distributions and intensities have often been found in large cities such as Beijing and Shanghai, which poses a new challenge in forecasting severe convective systems in urban regions due to the rapid development of urbanization. Guo et al. (2003, 2006b) studied the effect of urbanization on MCSs in the Beijing region using the MM5 model, and found that total precipitation in the urbanized region decreases, and its distribution tends to become concentrated and also intensified along the borderline between the urban and non-urban region. The precipitation intensity is also modified and locally distributed, and the high precipitation intensity core is found downwind of the city. This study is more consistent with those observed in this region. Thus, the urban region could act to create a bifurcation zone for precipitation distribution and produce more floods, as suggested by early studies.

The majority of the aforementioned studies focused on the dynamic forcing mechanisms related to urban land-use or change and did not address the potential role of aerosols. The aerosol particles in the cloud-forming air are one of the key factors in determining cloud and precipitation formation, which act as CCN or ice nuclei (IN). Thus, studies about the relations between aerosol and CCN are very important. With the increase of industrial air pollution and rapid urbanization in China, studies on aerosol–cloud interactions have also been conducted in recent years (e.g., Huang et al., 2003; Lou et al., 2003; Yao, 2006; Ma et al., 2007; Duan and Mao, 2008; Lei et al., 2008; Guo and Zheng, 2009). Furthermore, the effects of CCN on cloud formation in China have been modeled (e.g., Xu et al., 1983; Xiao et al., 1988; Zhao et al., 1998), and the impacts of sea salt and non-sea-salt sulfate on marine cloud microphysical properties investigated (Zhao et al., 2005a, b).

A cloud-resolving model including aerosol processes was used to study the effects of aerosols on the dynamics and microphysics of cloud (Fang, 2008), in which it was found that the increase of aerosol concentration suppressed the updrafts and downdrafts, and resulted in more (but smaller) cloud drops and more cloud water, which in turn lead to an increase in albedo. Smaller cloud drops have less efficient at coagulating to form raindrops and thus lead to less raindrop growth. For the whole cloud system, therefore, the impact of increasing aerosols inhibits precipitation. Guo et al. (2014) modeled aerosol impacts on summer convective clouds and precipitation over northern China by using the WRF model coupled with Chemistry (WRF–Chem) and found that the domain-averaged precipitation amount under polluted conditions can be increased up to 17% during the whole cloud lifetime. However, the maximum rainfall rate above 30 mm h^{-1} is enhanced, whereas that below 30 mm h^{-1} is suppressed in most cloud lifetime. The differences of cloud microphysics and dynamics between polluted and clean conditions indicate that both warm and ice microphysics and updraft are suppressed at the storm's initial and dissipating stages, whereas those at the storm's mature stage are obviously enhanced under polluted conditions.

Water-soluble dust particles can increase the concentrations of giant CCN, leading to earlier development of ice-phase precipitation particles, thus promoting the formation of precipitation (Yin et al., 2000; Chen et al., 2007; Yin and Chen, 2007; Chen and Yin, 2008). In addition, IN are very important in many weather events for the reason that IN can affect the initial concentrations of ice particles in cold clouds and then change the physical characteristics of cold clouds, which may inhibit the development of ice-phase precipitation particles (Yin et al., 2002; Chen and Yin, 2008, 2009).

WRF-based modeling studies have found that urban-induced aerosol pollution can result in a decrease in rainfall over the urban area, with the suppression occurring particularly in the downwind area (Fig. 1).

In addition, sensitivity studies using the WRF-Chem model have been conducted to investigate the effects of secondary aerosols formed by gaseous emissions of SO_2 and NO_2 on precipitation, and the results indicate that secondary aerosols can affect the intensity, duration and location of precipitation. Sulfate aerosol can increase the number of cloud droplets and enhance convection, and accelerate the formation of rain in the high cloud-water content region. In the low cloud-water content area, both SO_2 and NO_2 can inhibit precipitation, and NO_2 is the more efficient. Increasing SO_2 concentrations could lead to a dramatic effect on precipitation, in which the strong precipitation process is enhanced while the weak precipitation process is suppressed.

Recently, Jia and Guo (2012a, b) investigated the effect of pollutants on foggy events in China based on the WRF-Chem model coupled with local anthropogenic atmospheric pollution emissions, and indicated that the simulated fog distribution and intensity with anthropogenic emissions were closer to those observed. Polluted atmospheric boundary conditions were found to create favorable conditions for fog formation, increasing the fog area up to 50%, the maximum intensity by five times, and the duration to 1.5 h on average. The sensitivity studies showed that the secondary aerosols of SO_4, NO_3 and NH_4 formed from pollutant gaseous precursors of SO_2, NO_x and NH_3 had important impacts on the formation processes and microphysical structures of the foggy events.

2.2. *Field investigations of aerosols, CCN and cloud properties*

Field investigation of aerosols, CCN and cloud properties are important to reveal the connections of the background aerosol concentration, size distribution and chemical composition to clouds and precipitation formation processes, which is also critical for understanding cloud-seeding processes. China has conducted intensive field investigations on aerosols, CCN and cloud properties in the past several decades by using cloud-seeding aircraft equipped primarily with airborne particle measuring system (PMSs) or DMT. Airborne cloud measurements used in weather modification operations have developed rapidly in China. These probes have become the principal tools for characterizing aerosol and cloud particle properties, providing more detailed information on clouds and helping to improve weather modification operations.

Before 1980, Mee-130 instruments were used to measure CCN properties (e.g. Fan and An, 2000; You et al., 2002a). After 1980, the PMS was first introduced to China due to the need for cloud-seeding activities, but it was also used for observations of aerosols and cloud structures in both northern

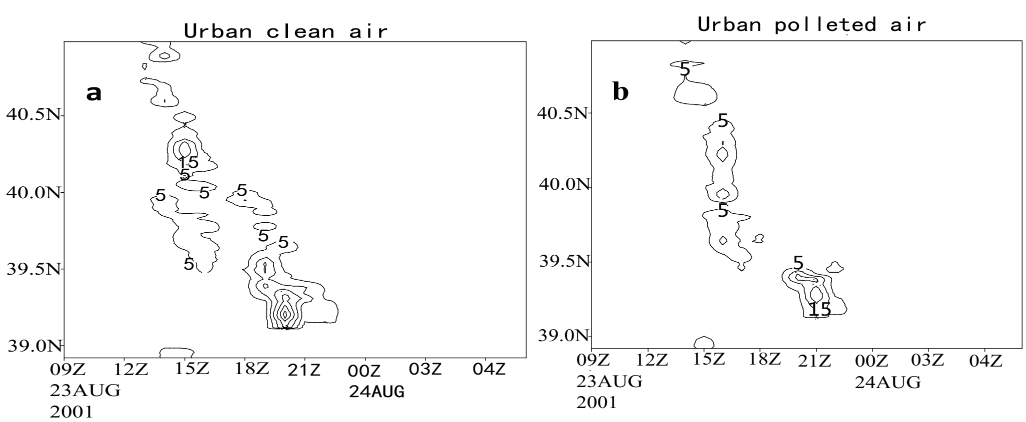

Fig. 1. Time series of the simulated rain rate under (a) clean urban air and (b) polluted urban air conditions.

and western China. Observational results have been reported in several papers (e.g., Li et al., 2003; Liu et al., 2003, 2005; Su et al., 2003a, 2003b; Wang and Lei, 2003; Wang et al., 2005; Yang et al., 2005; Jin et al., 2006; Li et al., 2006), and aircraft-based investigations of aerosol size distribution under cloudy and cloud-free conditions have been conducted in many regions of China (e.g., Zhou et al., 2004; Zhang et al., 2006; Zhao et al., 2006a; Fan et al., 2007, 2010; Qi et al., 2007; Zhang et al., 2007, 2011).

The observed data over northern China indicate that the CCN concentration is five times higher over urban areas than over rural villages (e.g., Shi and Duan, 2007; Duan and Mao, 2009). Observations in Beijing have shown that the concentrations of IN, which could be activated at -20°C, increased by about 15 times from 1963 to 1995 (You et al., 2002b).

The vertical distribution of aerosol number concentration and diameter sampled with the Passive Cavity Aerosol Probe (PCASP) on two cloud-free days in Beijing City showed that, under clear conditions, there was a strong accumulation zone of haze aerosols near the surface on both days. However, the number concentration on 12 September 2004 was much higher than on 29 August 2004 due to the effect of the strong inversion layer. The higher values of aerosol number concentration and diameter at 6000–6500 m were primarily due to the effect of upper-level dust flow in the northwestern region.

Lu and Guo (2012) investigated the aerosol distribution, source and relationship with CCN based on the Beijing Cloud Experiment (BCE) and indicated that, due to the different sources of aerosol, the conversion ratios of aerosol to CCN were less than 20% below 4500 m, and reached 50% above the level at 0.3% supersaturation (Fig. 4). The aerosols at higher levels (above 4500 m) were strongly affected by large-sized particles and those below 4500 m were strongly affected by local or regional pollution.

Measurements of microphysical properties of stratus cloud carried out by an airborne PMS in Hebei Province in October 1990 and April 1991 found that there is a positive correlation between aerosol number concentrations below the cloud base and cloud droplet number concentrations (Huang et al., 2005).

Aspects of cloud microphysics observed with PMS probes on four aircraft flights during August and September in 2003 in Beijing and surrounding regions showed that the maximum number concentration of small particles sampled with the FSSP-100 probe changed from 120 cm^{-3} for stratocumulus clouds to 183 cm^{-3} for deep altostratus clouds, and the mean diameter was around 7.22–16.05 μm (Zhang et al., 2007). The data of the 2D-GA2 probe showed that the maximum number concentration of large particles changed from 2.25×10^{-3} cm^{-3} to 3.29×10^{-1} cm^{-3}. The maximum water content explored with the King-LWC probe was 0.42–0.69 g m^{-3} in stratocumulus clouds.

Both the vertical and horizontal distribution in stratiform clouds showed clear inhomogeneous features; high number concentrations of small particles of >120 cm^{-1} existed in the upper levels (above the -10°C level), but also with some larger sized particles (maximum size reaching 20 μm). The liquid water content decreased slightly with height and also kept to around 0.1–0.2 g m^{-3}. The layers between -5.9°C to -8°C were composed of a large number of column ice crystals and a small number of riming particles. Those between -8°C to -12°C were almost rimed particles, and those above -20°C were primarily dentritic ice particles. The number concentration of large-sized ice particles was around 0.01–1 L^{-1}. The layer-averaged size distributions of cloud particles were quite different in stratocumulus and stratus cloud.

The large particles followed a unimodal distribution in stratocumulus cloud, and the width of the spectrum reached approximately 1500 μm. A low number concentration corresponded to a low layer of cloud. However, layer-averaged size distributions in stratus cloud was quite different; for particles less than 400 μm in diameter, the size distribution averaged over the layers of 0°C to -8°C and -8°C to -12°C were almost the same, while for particles larger than 400 μm in diameter, the size distribution averaged over the layers of -8°C to -12°C had an obvious bimodal-type distribution, and that over the layers of 0°C to -8°C had a multi-modal-type distribution. The width of the spectrum was around 1300–1400 μm.

Anthropogenic aerosols might contribute significantly to the observed reduction of precipitation over northern China, and provide a possible feedback cycle of aerosol loading and precipitation that produces considerable harmful impacts on air quality, the hydrological cycle, crops, and other environmental problems. Statistical analyses of historical precipitation and aerosols data have revealed that deeper precipitation clouds can be influenced by aerosols in the form of precipitation suppression. In particular, the suppression effect is stronger over mountainous areas than over plains, and the influence of anthropogenic aerosols on convective precipitation possibly plays an important role in summer over northern China (Zhao et al., 2006b; Dai et al., 2008; Duan and Mao, 2009).

In addition, satellite [e.g. Moderate Resolution Imaging Spectroradiometer (MODIS)] data have also been used to study aerosol–cloud interactions, and have been successful in obtaining aerosol optical depth and cloud effective radius information (e.g. Chen et al., 2004; Zhao et al., 2006b).

Li and Mao (2006) analyzed cold cloud reflectivity in China during the period 1982–1999 using the PAL (NOAA/NASA Pathfinder AVHRR Tiled Land Data), and found that the cold cloud reflectivity could have changed over some areas during this period, and, in the case of the Beijing area, cold cloud reflectivity could have changed nonlinearly under the influence of IN.

By analyzing satellite data from the International Satellite Cloud Climatology Project (ISCCP), MODIS, and the Clouds and the Earth's Radiant Energy System (CERES), Huang et al. (2006a, 2006b) found that, on average, the ice cloud effective particle diameter, optical depth, and ice water path of cirrus clouds under dust-polluted conditions are 11%, 32.8%, and 42% less, respectively, than those derived from ice clouds in dust-free atmospheric environments; and a significant negative correlation exists between dust storm index and ISCCP cloud water path, and the semi-direct effect may play a role in cloud development over arid and semi-arid areas of East Asia and contribute to the reduction of precipitation.

2.3. *Climatology and variation of cloud water retrieved from satellite data*

Cloud water is a key component in cloud physics and weather modification. Although the critical role of cloud water has been widely recognized, its quantitative analysis has been limited because of insufficient observations. Surface observations of cloud have served as the primary source of information about clouds in the past. However, these surface datasets do not really provide enough information on cloud properties, such as cloud water and cloud optical thickness. Owing to the expense and difficulty of observations, field experiments only provide short-term cloud water data, but have nevertheless extended our knowledge about cloud processes and helped to validate numerical models.

Measurements of cloud properties from satellites can supplement surface observations and *in situ* studies by extending their results to larger spatial and temporal scales, as well as by providing more cloud parameters, including cloud water. The ISCCP was established in 1982 as the first project of the World Climate Research Program (WCRP) to collect and analyze a globally uniform satellite radiance dataset to produce new cloud climatology. With the implementation of ISCCP, climatic research on cloud water, presented as cloud water path (CWP) in the ISCCP, as well as the hydrological cycle involving CWP, became possible.

Yu et al. (2001, 2004) analyzed the cloud amount and cloud optical depth over southeastern China using ISCCP D2 data and found that the low- and mid-cloud maxima of both cloud amount and cloud optical depth occur in winter and early spring, and suggested the effect of the Tibetan Plateau on the westerly flow as being the cause of different cloud characteristics. In winter, westerly flow prevails and covers the Tibetan Plateau. The plateau forces the westerly flow to go around it in the low levels, and then the two parts of the circumnavigating plateau flow converge downstream. In the middle level, the surface friction of the Tibetan Plateau causes divergence (Yu et al., 2004; Li et al., 2004, 2005). As a result, large-scale lifting occurs on the lee side of the plateau and results in the formation of stratiform cloud in southeastern China.

Li et al. (2008) studied the climatology and variation of cloud water using ISCCP D2 data. The spatial distributions of annual mean CWP derived from ISCCP D2 and precipitation derived from GPCP V.2 for the period 1984–2004 exhibit broad similarity in China (Fig. 2). The close relation between cloud water and precipitation is in many ways tied to large-scale dynamical patterns and topographical features, and the difference in the Sichuan Basin exhibits a distinct mechanism in cloud formation and the cloud water cycle.

The seasonal means of cloud water reflect the change of circulation over China. In winter, the CWP distribution pattern is similar to that of the annual mean, with great contrast between northern China (northeastern and northwestern China) and southern China (southeastern and southwestern China). The area of high CWP values covers almost all of southeastern and southwestern China. In northeastern and northwestern China, CWP is less than 0.03 kg m^{-2} due to cold temperatures and insufficient water vapor transport. In summer, the water vapor brought by the summer monsoon circulation largely affects southwestern China, and the average CWP of this region rises in general. The minimum CWP is still held in northwestern China because of the blocking effect of the Tibetan Plateau.

The transition of circulation from westerly flow to monsoon circulation can be distinguished from the low CWP values in southeastern China, because in summer the westerly flow shifts northward and there is no large-scale lifting, which favors the formation of clouds. In spring and autumn, the CWP distributions are under the influence of the respective previous seasons. These two seasons share a similar distribution pattern in northeastern and northwestern China. In southeastern China, an apparent difference in CWP distribution between spring and summer is found, through which the weakening topographical influence and the enhancing monsoon circulation influence are identified. In autumn, the sudden shift of the westerly and easterly flow results in the in-

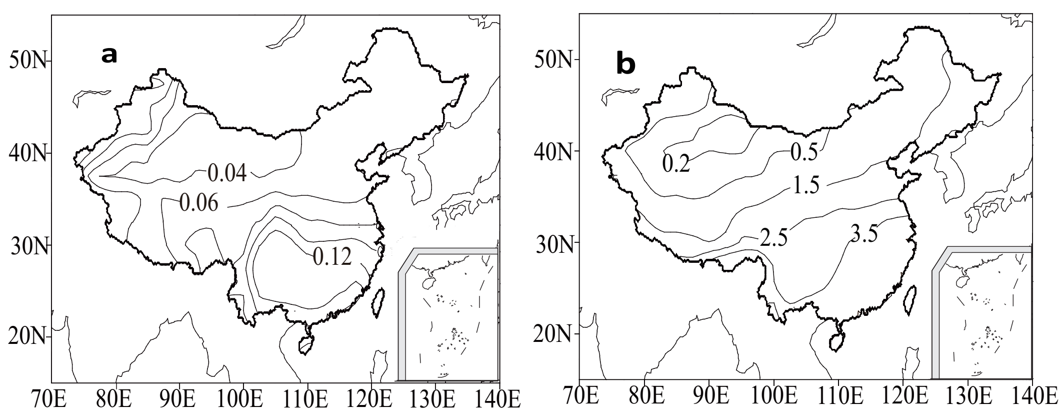

Fig. 2. (a) Annual mean cloud water (kg m^{-2}) for the period 1984–2004. Panel (b) is the same as (a), except for precipitation (mm d^{-1}) from GPCP V.2.

crease of CWP on the lee side of the Tibetan Plateau and the decline in northeastern and northwestern China.

By calculating the linear trend of annual mean CWP from 1984–2004 (Fig. 3a), an increase in CWP can be found in China, with the largest increases occurring in the eastern Tibetan Plateau and the western part of northeastern China, where the linear trends are about 0.015–0.025 kg m^{-2} (10 yr)$^{-1}$. Over the south part of Xinjiang, mainly in the desert region, CWP decreases by about 0.005 kg m^{-2} (10 yr)$^{-1}$. The rates of increase over southeastern China and northwestern China are relatively small. Considering the differences in CWP distribution, percentage trends have also been examined (Fig. 3b). The largest percentage linear trends, larger than 32% (10 yr)$^{-1}$, are found in the Tibetan Plateau and the western part of northeastern China. Decreasing trends in CWP are found in the desert areas in the western part of northwestern China and adjacent areas.

From the above analyses of the linear trend, the primary regions with increasing trends are located in the eastern Tibetan Plateau and adjacent areas. These increasing trends of CWP are related to the water vapor variation in the Bay of Bengal, which is the main water vapor source in China. Trenberth et al. (2005) analyzed the water vapor in four datasets (SSM/I, ERA-40, NCEP-1 and NVAP) from 1988–2001 and found an increasing trend in the Bay of Bengal in all of them. Zhai and Eskridge (1997) calculated the linear trend and percentage linear trend of water vapor from 1970–90 using Chinese radiosonde data, and obvious increases were found in the eastern Tibetan Plateau and southwestern China. According to these facts, the increases of CWP can be reasonably linked to the increases of water vapor.

In summer, the largest increase in CWP in China occurs in the eastern Tibetan Plateau. In northeastern China and the northern part of Xinjiang, CWP decreases by about 5% and 10% (10 yr)$^{-1}$, respectively. Wang (2001) and Lü et al. (2004) showed that the summer monsoon circulation has been weakening since the end of the 1970s. During the weakening period of the summer monsoon circulation, the location of the subtropical high has been farther south and induced circulation that barely transports any water vapor westward through the mountains in the northern part of Xinjiang. Insufficient water vapor and the blocking effect of the mountains are the possible reasons for the decreasing trends in northwestern China. As for northeastern China, decreasing water vapor transport caused by the same factors can explain the negative CWP trend in summer. The weakening summer monsoon circulation has also caused the drought over North China and flooding along the middle and lower reaches of the Yangtze River after the 1970s. A relatively large trend of increase occurs in winter. The largest linear trend is located mainly in northeastern China, characterized by a 60% (10 yr)$^{-1}$ rise. In southeastern China, CWP increases slightly by less than 15% (10 yr)$^{-1}$. The increasing trends of CWP in winter are consistent with the trends of water vapor in the distribution pattern (Zhai and Eskridge, 1997), which is considered to be caused by the rises of temperature in winter.

2.4. *Cloud-seeding activities and its scientific basis in China*

2.4.1. *Current status of operational weather-modification programs*

Operational weather-modification programs, which primarily involve cloud-seeding activities aimed at enhancing precipitation or mitigating hail fall, exist in 30 provinces across China. The funding that supports these operational activities is primarily from local government, but central government and some enterprises such as hydroelectric power, tobacco and other economic crop companies, have also begun to support weather-modification operations in recent years. China now mainly conducts glaciogenic cloud seeding rather than hygroscopic cloud seeding. In recent years, China has also begun experimenting with hygroscopic cloud seeding using hygroscopic flares, but this approach is not yet employed operationally.

A cloud-seeding activity can only be successful if the right amount of seeding material is delivered to the right location at the right time, and for the right time interval. Therefore, the development of highly reliable seeding tools is essential. A relatively rapid advancement in cloud-seeding

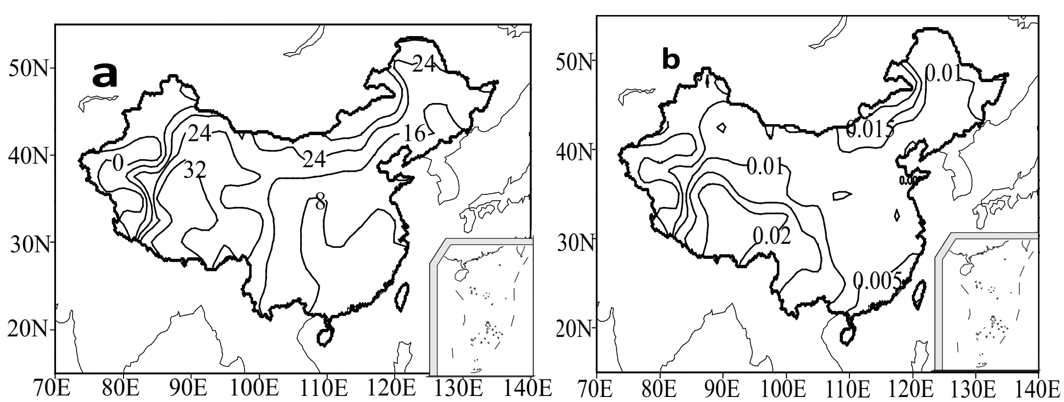

Fig. 3. (a) Linear trend of annual mean CWP [kg m^{-2} (10 yr)$^{-1}$] for the period 1984–2004. Panel (b) is the same as (a), except for the percentage linear trend [% (10 yr)$^{-1}$].

tools, including aircraft, rockets, artillery and ground-based generators, has taken place in the last decade in China (Fig. 4).

Well-equipped advanced aircraft cloud seeding is mainly organized and conducted by provincial weather modification offices. Stationary and mobile AgI-rocket launching systems have been widely used in weather modification activities, and artillery-seeding with AgI-shells is still used for hail suppression in some regions. The rockets used for cloud seeding usually contain AgI of 10–15 g, while ground-based generators are used in some mountainous regions in China. Although ground-based generators have many advantages, such as high safety levels and a low influence on air traffic, uncertainty exists with this approach insofar as whether or not the released seeding agent can actually reach the intended target.

2.4.2. *Operational cloud-seeding guidance and evaluation*

The scientific guidance and evaluation of cloud seeding are key components in operational weather-modification activities. Most provinces in China have established weather modification operational systems, which include basic information from meteorological networks such as radar, satellite, sounding, automatic meteorological and rain gauge stations, as well as position information from seeding tools to guide cloud-seeding operation. In recent years, GPS has been widely used in aircraft cloud-seeding activities in China. The combination of GPS with remote sensing data (e.g. meteorological radar, satellites etc.) and GIS greatly improve the cloud-seeding ability and decease the blindness of cloud-seeding activities. GPS, remote sensing and GIS techniques for tracking and guiding cloud seeding have become increasingly popular in cloud-seeding activities in China. Accordingly, weather-modification experts can guide aircraft cloud seeding from ground-based real-time cloud information observed by radar and satellites etc., instead of doing so onboard the aircraft.

One of the most advanced and popular instruments to guide cloud seeding is the Doppler radar network, which covers the major regions of the country. For example, the radar mosaic system used in Beijing weather modification was developed based on seven radars in and surrounding Beijing City (Fig. 5). The mobile polarization Doppler radar is also starting to be used in cloud observation and weather modification experiments (Fig. 6). These capabilities are of great value in identifying the types of particles in a cloud, and are of potential application in assessing cloud-seeding experiments since the particle classifications derived from this radar can be used in many aspects of weather modification, such as to reveal the transformation of supercooled liquid water droplets to ice crystals in glaciogenic seeding and the development of large drops in hygroscopic seeding, and to identify hailstorms and non-hail storms in hail-suppression seeding.

The current polarization radars, including C-band and X-band, are available in national cloud and weather modification research projects and also in some provinces such as Beijing, Anhui and Hubei, but will expand rapidly in numbers in

Fig. 4. Seeding tools widely used in current weather-modification operations in China: (a) aircraft quipped with AgI flare agents; (b) ground-based AgI generator; (c) stationary AgI-rocket launching system; (d) mobile AgI-rocket launching system.

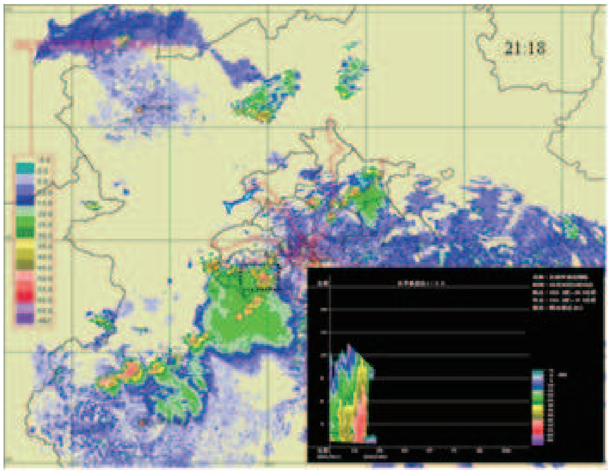

Fig. 5. Radar mosaic system used in the Beijing weather modification office, which incorporates seven radars in and surrounding Beijing City.

Fig. 6. X-band polarization Doppler radar used in field experiments operated by the Institute of Atmospheric Physics, Chinese Academy of Sciences.

operation in the future. The millimeter-wave cloud radar with wavelengths of 8 mm has also begun to be used in cloud observation, but not popularly at present.

Retrieval information suitable for cloud-seeding operations from different satellites and ground-based GPS-network receivers has also progressed rapidly in recent years (Ma et al., 2007). Satellite retrievals have successfully been used to identify cloud-seeding effects in China (Rosenfeld et al., 2005; Yu et al., 2005). NOAA Advanced Very High Resolution Radiometer (AVHRR) images have revealed conspicuous tracks of glaciated cloud in thick supercooled layer clouds induced by cloud seeding over central China, which is the third and most detailed report of the effects of advertent cloud seeding for precipitation enhancement being detected and analyzed based on satellite observations, and it opens new possibilities of using satellites for directing and monitoring weather modification experiments and operations (Rosenfeld et al., 2005).

In some provinces, cloud-seeding aircraft have advanced airborne PMS instruments, which can directly explore the background aerosol size distribution and cloud structure, and determine suitable seeding conditions. More than 10 cloud-seeding aircraft have mounted PMS (DMT) instruments in China.

An additional instrument equipped in Chinese weather-modification operations is the ground-based and airborne microwave radiometer (e.g., Lei et al., 2003; Jin et al., 2004). Since the dual-channel microwave radiometer can retrieve the path-integrated total amount of liquid water and water vapor along its beam by simultaneously measuring emissions from vapor and liquid at frequencies near 21 GHz or 23 GHz and 31 GHZ, it has a more important application in weather modification. However, this instrument is not efficiently used in locating regions of high supercooled liquid water in natural clouds in weather-modification operations due to a lack of validation and improvements of relevant retrieval techniques. More sophisticated ground-based multi-channel microwave radiometers with capabilities in observing water vapor, liquid water, temperature and humidity have been used in recent weather-modification operations (Fig. 7).

Cloud-resolving models play an important role in cloud-seeding activities. These models can be used in many aspects, such as seeding design, seeding guidance and seeding evaluation. At the National Weather Modification Centre (WMC) of the China Meteorological Administration (CMA), real-time operational weather modification models based on mesoscale cloud-resolving weather forecasting models such as MM5, WRF and GRAPES have been established to guide weather-modification operations (Lou et al., 2012). These models are modified to predict and output information on cloud structure and evolution, such as supercooled cloud water etc. (Fig. 8), or are coupled with AgI nucleation processes, which is import to judge cloud-seeding potential and evaluate seeding effectiveness. Some provinces are also operating one of these models to guide local cloud-seeding operations.

2.4.3. *Scientific basis for glaciogenic seeding*

Glaciogenic seeding is the process of enhancing ice content in clouds either by nucleating new ice crystals or freezing supercooled cloud droplets. The current seeding agents for glaciogenic seeding in China are silver iodide (AgI), solid or liquid carbon dioxide (dry ice), and liquid nitrogen.

The seeding material is one of the most important factors to determine effective cloud seeding. Silver iodide and dry ice have been the most widely used in field projects and the most thoroughly tested in the laboratory, yet some aspects of their ice nucleation behavior as well as the interaction mechanisms between the microphysics and dynamics of a seeded cloud are still not completely known. The important advantage of the coolant agent is that the number of generated ice crystals is nearly independent of the temperature. By dry-ice seeding, a vertical generated ice crystal plume tends to cause an organized rapid upward motion of the plume (e.g., Kraus and Squires, 1947) due to vertical integration of the buoyant

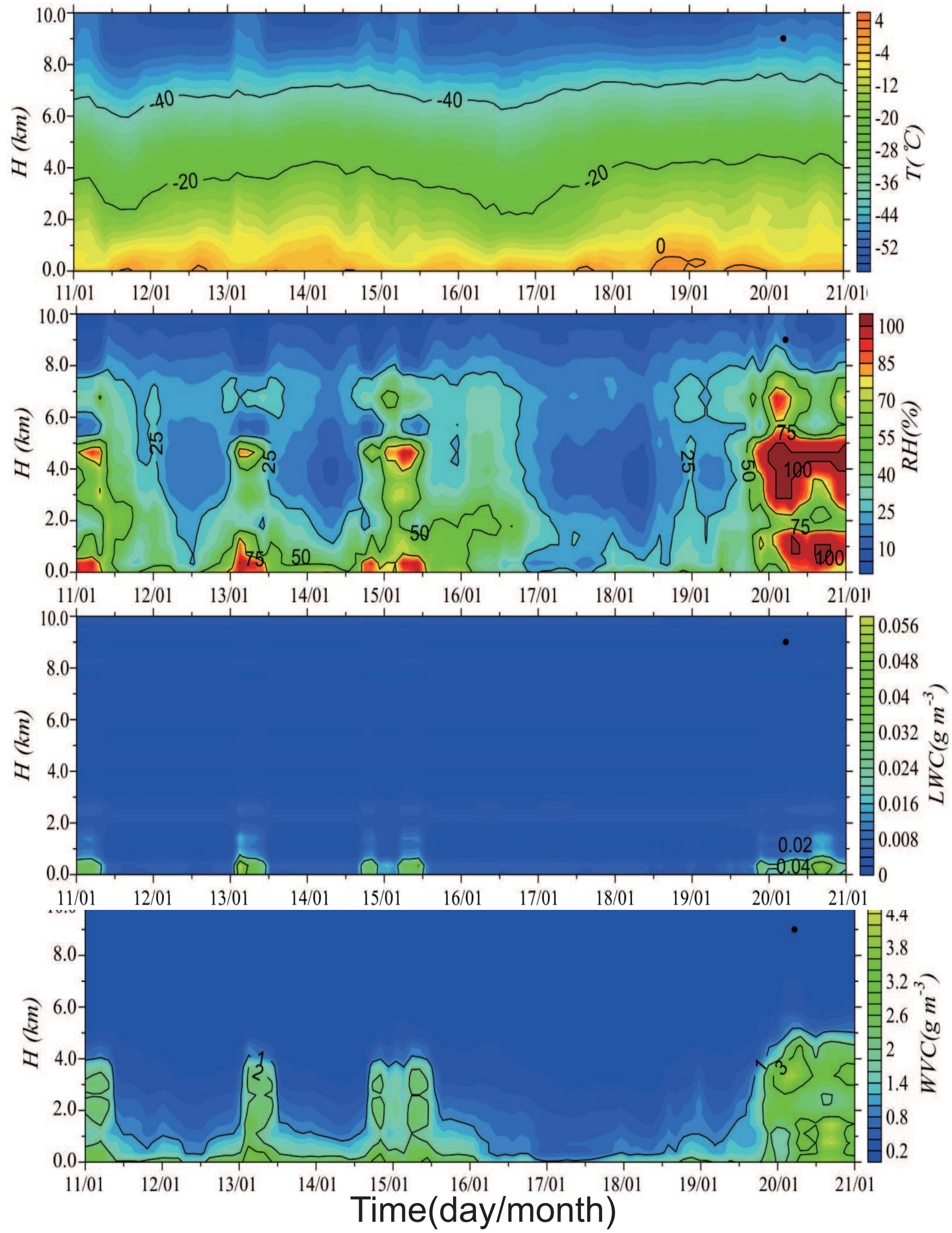

Fig. 7. Time–height distribution of temperature (T), relative humidity (RH), liquid water content (LWC) and water vapor content (WVC) sampled by a multi-channel microwave radiometer for a fog process on January 11–20, 2013 in Beijing city.

force. However, dry-ice seeding has a dynamic shortcoming due to its rapid fall speed, which reduces the ice crystal growth time by fast updraft development within vertically oriented ice thermals (Schaefer, 1946). The number of ice crystals formed by the nucleation of AgI increases drastically as the temperature in the atmosphere decreases (e.g., Vonnegut, 1947; Garvey, 1975), and also suffers from weak dynamics at low altitude due to a lack of ice nucleation. Since dry-ice pellets have a rapid fall speed and have to be dropped from high altitudes, Fukuta (1996a, b) suggested a method to seed the liquid-CO_2 horizontally at the lower level of the supercooled portion of clouds. His original physical idea of the liquid CO_2 is to maximize the interaction time of the rising thermal produced by seeding with the abundant supercooled water at the lower level of clouds and to induce a larger dynamic effect.

Many Chinese researchers have investigated the AgI-seeding effect on cloud dynamics and microphysics by using cloud models (e.g., You et al., 2002b; Fang, 2004; Chen et al., 2005; Fang et al., 2005a, b; Li et al., 2006; Hong and Zhou, 2006; Guo et al., 2006b, 2007; Hu et al., 2007). These models have parameterized microphysics incorporated with the AgI nucleation process. The results have shown that cloud seeding may lead to changes in the dynamics and microphysics of a cloud.

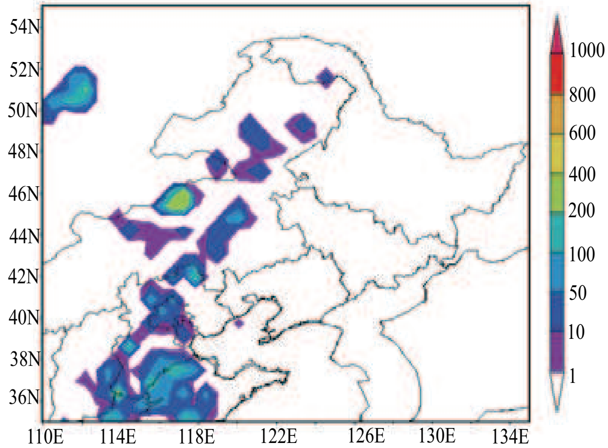

Fig. 8. Distribution of column supercooled water (g m^{-2}) at 0900 UTC 1 May 2009 predicted by an operational weather-modification model, which was used to guide rain enhancement for a fire fight in northern China. The cloud system moved from southwest to northeast.

We also compared the effect of the liquid-CO_2 seeding technique proposed by Fukuta (1998) with AgI-seeding on cloud dynamics, cloud microphysics and precipitation evolution by developing a 3D cloud model with nucleation processes of liquid-CO_2 and AgI. The results showed that the seeding by liquid CO_2 and AgI at the cloud levels of $-15°$C to $-20°$C has almost the same dynamic effect on the simulated clouds. The seeding is able to induce the formation of weak convective cells in both seeded and unseeded regions due to latent heat released by the transformation from liquid saturation to ice saturation. However, the initial seeding conducted by liquid CO_2 in the region of maximum supercooled water with a temperature of 0°C to $-5°$C enables the production of a much stronger dynamic effect and precipitation by forming many new convective cells at low levels in the later stages of seeded clouds. Twin-rotating rings are initially formed at lower altitudes of about 4–6 km above ground level in the downstream region near the seeded area. Owing to the effect of stable upper levels, the rings move horizontally along the levels of 4–6 km. By 60 min, the most prominent feature is that the up- and downdrafts meet at around 4–6 levels and force the air to move horizontally, and another obvious ring is formed in the upstream region. This process is favorable for the transition of water vapor to cloud vapor, and also the glaciation of supercooled water into ice.

Using the same cloud model with the AgI seeding process, sensitivity experiments were conducted to look at responses of cloud dynamics, microphysics and precipitation to different seeding methods with different seeding locations, times and agent amounts. The results showed that the cloud microphysical variations responding to different seeding methods differ greatly. The seeding leads to a decrease in the formation of cloud ice, and it enhances snow formation in the cloud development and maturation stage. It is recommended that cloud seeding conducted in the regions of maximum updraft and supercooled water in convective cloud may maximize the augmentation of surface precipitation.

To better understand the variation of cloud and precipitation induced by seeding in a mesoscale manner, the cloud seeding processes in a cloud model (Guo et al., 2006b) were incorporated into the WRF model to study the mesoscale cloud and precipitation development, and focus on the targeting of seeding agents, the diffusion and transport of seeding material, the dynamic and static effects on the cloud system, and evaluating precipitation on the ground induced by seeding. The results showed that the supercooled cloud water is almost depleted in the seeded region and increased above it due to dynamical effects. The ice number concentration increases rapidly. The seeding leads to a decrease of graupel and enhances snow formation at the same time. The seeding also enables a redistribution of the accumulated precipitation at the surface and a change in the total precipitation (Fang and Guo, 2007; Fang et al., 2009).

2.4.4. *Scientific basis for hygroscopic seeding*

The aim of hygroscopic seeding is to promote water droplet growth through coalescence and thereby improve the efficiency of the rainfall formation process. Earlier hygroscopic cloud seeding in China was based on the direct use of salt powder. However, due to the need for huge amounts of salt powder for each cloud seeding operation, and also the harmful effects on the aircraft itself, hygroscopic seeding ceased in China until recent years.

Statistical, observational and modeling results for larger particles (e.g., > 10 μm diameter) have provided some evidences for hygroscopic seeding (Silverman and Sukarnjanasat, 2000). Field experiments or operations, such as those in South Africa and Mexico in which hygroscopic seeding flares were employed, have shown remarkably similar statistical results in terms of the differences in radar-estimated rainfall for seeded versus non-seeded groups (Silverman and Sukarnjanasat, 2000), and an increase in rain mass 30–60 minutes after seeding was found. A delayed response in radar-derived storm properties is a possible function of seeding-induced dynamic processes beyond the classical cloud physics results that links cloud condensation nuclei and droplet spectra to rain production (WMO, 2000). Hygroscopic seeding experiments have provided statistical support for rainfall increases due to seeding based on single cloud analyses, but the physical processes leading to these increases in precipitation are not well understood.

The size of seeding particles is considered to play a critical role in hygroscopic cloud seeding and warm rain enhancement since the cloud condensation nucleation and coalescence processes are found to closely relate to the size of aerosol particles. Johnson (1982) reported that giant (> 1 μm in radius) and ultragiant (> 10 μm in radius) aerosol particles will produce a tail of large drops in the cloud-droplet distribution, and then these drops will significantly accelerate the development of precipitation via the coalescence process. Yin et al. (2000) showed that the coalescence between water drops can be enhanced by adding giant cloud condensation nuclei, and found that the most effective particles were those with radii larger than 1 μm, especially those larger than 10 μm. Zhang et al. (2006) suggested that the role of giant CCN on precipitation formation in warm, stratiform clouds is only important when the concentrations of CCN larger than 5 μm are high. However, some studies have shown that particle size might not be essential to the formation of raindrops for some clouds, such as a maritime cloud (Takahashi, 1976; Takahashi and Lee, 1978).

Owing to the inconsistent conclusions obtained in previous studies, further investigations are necessary by designing more detailed numerical experiments, as well as field measurements (Orville, 1996; Bruintjes, 1999; Ma et al., 2007; Guo and Zheng, 2009).

The effect of hygroscopic seeding was studied based on 1D cloud model, and it was shown that seeding can apparently alter cloud spectra and enhance precipitating particle formation. The effect of different sizes of seeded particles on precipitation is shown in Fig. 9. It shows that different sizes of seeded particles have different impacts on precipitation formation, in which the seeding of larger-sized particles (e.g., particle sizes larger than 2 μm in diameter) has a more obvious effect on precipitation formation.

To further clarify the effect of hygroscopic seeding, a WRF-based mesoscale cloud seeding model was developed to investigate the effects of giant particle cloud seeding on cloud microphysics, dynamics and precipitation. The cloud formation, intensity and evolution as well the spatial and temporal distributions of seeded and non-seeded clouds were presented and compared. The study area was chosen around Beijing urban regions where the aerosol background number concentration was around 1026 cm^{-3}, which was primarily produced by air pollutants and composed of small-sized particles. The seeded aerosol number concentration was 1000 cm^{-3} with sizes larger than 1 μm in diameter, which were referred to as giant particles in the study. The seeding duration was 10 min, beginning from 0730 LSTnd ending at 0740 LST. The seeding height was at 2.5–3.5 km, which was located just near the cloud base. The WRF model was initialized with NCEP data and run for 24 hours.

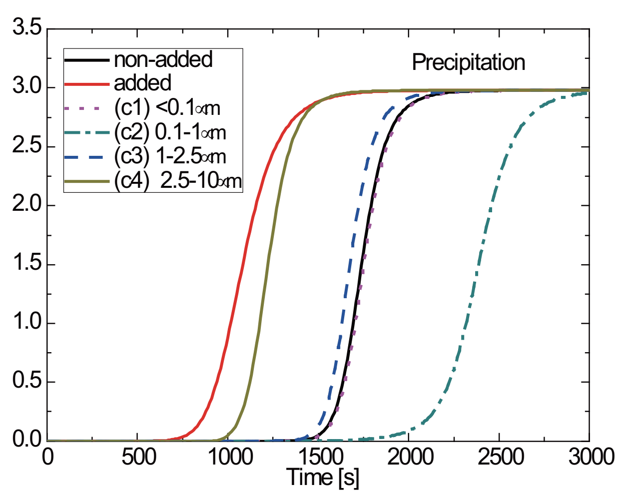

Fig. 9. Effect of different sizes of seeded particles on precipitation.

Comparing the non-seeded case with the seeded case, we found that the cloud seeding with water-soluble aerosols of sizes larger than 1.0 μm in diameter may induce substantial changes in cloud microphysics, dynamics and precipitation. The indication was also that seeding has a high impact on cloud ice processes, such as increased ice particle concentrations. The influential time for seeding is around 3–4 hours. The maximum surface rain intensity, rain amount and the accumulated precipitation are greatly changed, in which the rain intensity is increased, but the maximum precipitation amount is decreased and surface accumulated precipitation is increased. The maximum increase of surface accumulated precipitation can be 41%. The surface precipitation distribution is also changed from the concentrated type for the non-seeded case to the more dispersed type for the seeded case (Fig. 10). The precipitation distribution for the seeded case indicates an apparent precipitation increase in the "extra-area" and "downwind area".

2.4.5. *Scientific basis for hail suppression*

Cloud seeding for hail suppression is the second most frequent weather-modification activity in China. The scientific basis for hail suppression in China follows two main mechanisms: one is based on the so-called beneficial competition mechanism by over-seeding of the ice nucleus, and the second is the explosion mechanism induced by artillery. Although the latter has not been scientifically confirmed in the weather-modification community, the practical use of this method is still popular in China.

Researchers have developed an AgI-seeding process in a 2D hail cloud model to simulate the seeding effect on hail suppression (Huang and Xu, 1994). The AgI-based nucleation processes such as deposition and contact freezing are included in the model to investigate the seeding effects on hail suppression with various hailstorms and seeding methods. The possible effect of explosion that causes the raindrop breakup on hail suppression has also been discussed (e.g., Duan and Xu, 2001) using a 2D hail model. AgI-based nucleation processes have also been developed in a hail-bin model (Guo et al., 2003) to study the seeding effect on the hail suppression mechanism (Guo et al., 2004; Xiao et al., 2006). These studies show that, if appropriate seeding methods are used, the effect of seeding on hail clouds can significantly suppress hail formation by causing early and increased precipitation of rain. The application of hail-cloud models in the early identification of hail-cloud has also been conducted in China (Yu et al., 2001; Xiao et al., 2002; Li et al., 2003).

One of the key issues for operational hail suppression activities is to identify hailstorms and non-hail storms. Chinese scientists have developed identification criteria for this purpose based on field experiments (Table 1). The criteria for identifying strong hailstorms are quite good and the accuracy rate can reach more than 90%.

In recent years, dual-polarized radars have been used in hail-suppression operations. Figure 11 is an example of the Range Height Indicator (RHI) scan of a hail cloud. The location of hail formation is quite clear and can be a good index

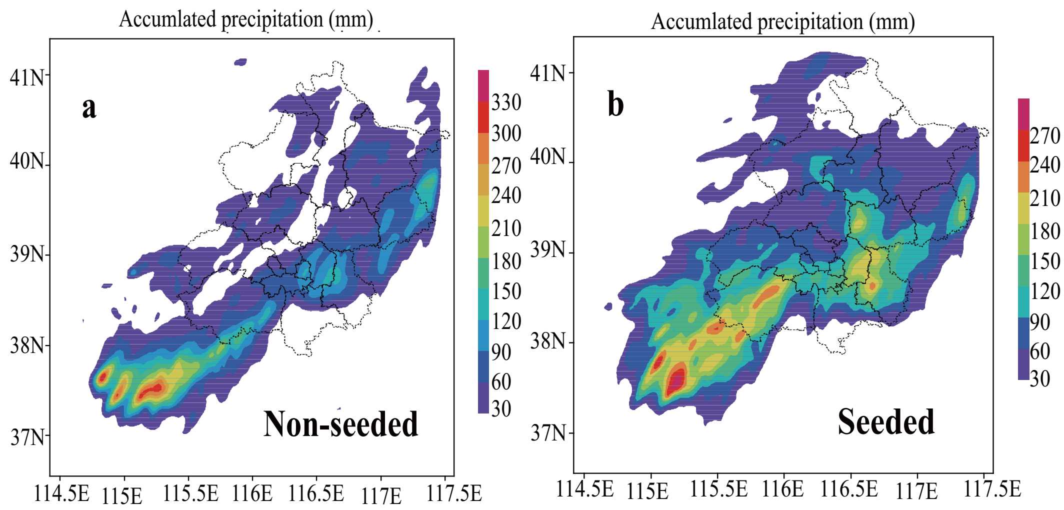

Fig. 10. The surface accumulated precipitation distribution derived from the WRF-based cloud seeding model for the (a) non-seeded case and (b) seeded case.

Table 1. Identification criteria for hailstorms and non-hail storms in western China.

Cloud type	H_{45dBZ} (km)	T_{45dBZ} (°C)
Strong hailstorm	$\geqslant 8.0$	$\leqslant -20$
Weak hailstorm	7.0–8.0	-14 to -20
Thunder clouds	< 7.0	> -14

H_{45dBZ}, height of the top of the RHI radar echo with intensity > 45 dBZ; T_{45dBZ}, corresponding sounding temperature.

for cloud-seeding operations.

Although significant progress in the theoretical modeling of hailstorms, especially in modeling hail-cloud microphysics, hail formation mechanisms and the seeding effect, has been made in recent years in China, there are still many open questions that require clarification. Mesoscale cloud models with detailed hail microphysics and with realistic seeding routines should be applied during all stages of the forecasting, operation and evaluation of hail-suppression activities. The prediction ability of time, location and amount of hailfall in hailstorm models should be further improved. Conducting detailed comparisons between observed and simulated results of hailstorms is necessary in order to improve the physical processes in hail-cloud models.

3. Discussion and conclusions

Over the past several decades, great efforts and progress in cloud physics and weather modification have been made in China, including studies on cloud modeling, cloud microphysics and dynamics, aerosol–cloud interactions, MCSs, severe wind formation, and weather modification.

More advanced cloud models with detailed microphysics and mesoscale cloud-resolving models have been developed and applied to guide cloud-seeding operations, as already done in many other countries outside China (e.g., Tzivion et al., 1994; Bruintjes et al., 1995; Orville, 1996).

The modern techniques of GPS, remote sensing and GIS have been widely used in operational cloud-seeding programs in China, and have greatly decreased the blindness and uncertainties in weather-modification activities. In addition, cloud models with glaciogenic and hygroscopic cloud-seeding processes have been developed and used in order to understand the variations in cloud microphysics, dynamics and precipitation induced by cloud seeding. Furthermore, we have also seen a rapid increase in the interest in this area due to the strong demands for fresh water and a wide variety of disaster prevention programs.

Despite significant advances in relevant subjects of cloud physics and weather modification in recent years in China, there are still many deficiencies or challenges left to be addressed, such as gaining a better understanding of cloud and precipitation formation mechanisms, improving the seeding efficiency and seeding techniques, and obtaining more reliable evidence of seeding effectiveness, as indicated in some other publications (National Research Council, 2003; List, 2004; Garstang et al., 2005). The potential for progress in cloud physics and weather-modification research is dependent upon improved cloud model treatments of cloud physics and precipitation, their resolution and initialization via observational data and data assimilation techniques, and also upon applying advanced observational technologies and accurately retrieving information from remote sensing data.

China is the largest country to conduct an operational weather-modification program in the world. Comparing the field with that outside China (National Research Council, 2003), the weather-modification activities in China have some unique features, one of which is the application of multiple advanced seeding tools in weather-modification activities, such as aircraft, ground-based rockets, artillery and generators. These seeding tools can realize seeding operations in different cloud systems from stratiform clouds to severe convective clouds such as hailstorms. Rocket-based seeding can

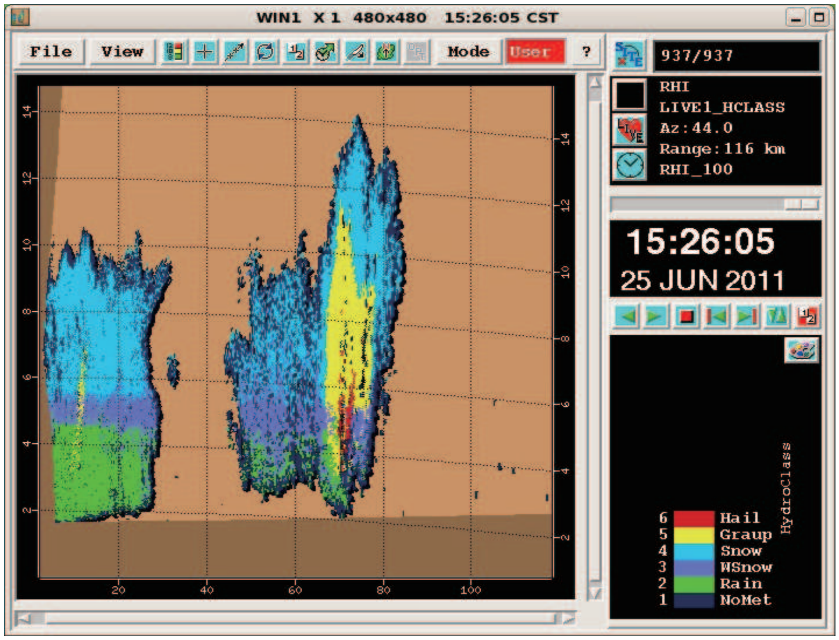

Fig. 11. RHI scan of the cloud particle classification results obtained from a newly established dual-polarization radar. The red coloring shows the hailstones formed from graupel particles above (yellow coloring). The melting level is obvious in the figure.

directly and promptly deliver seeding material into the targeted area of severe clouds, which is impossible or difficult for aircraft seeding due to security reasons. Therefore, the development of reliable rocket and advanced cloud monitoring systems are critical to achieve successful seeding results.

Another feature is that operational weather-modification activities in China are mainly conducted to meet emergency needs in places that suffer severe drought and hail-related disasters, as compared to some countries who usually conduct cloud-seeding experiments in a fixed location. Therefore, to conduct long-term, well-designed and randomized cloud-seeding experiments is quite difficult via the operational cloud-seeding program. The evaluation of seeding effectiveness has to depend on comparisons of rain gauge data between target and control areas, as well as on physical evaluations of targeted clouds by radar or other observational data. To meet statistical requirements, the selection of a control area is often difficult in places lacking climatic rain gauge data.

In the past ten years, we have witnessed rapid development of a multitude of advanced tools used for observing and seeding cloud systems in China. This progress provides an effective way to explore cloud structure and identify seeding targets, as well as determine effective seeding locations. It is becoming possible to conduct detailed studies on the chain of physical events involved in the effects induced by cloud seeding. Reducing key uncertainties in weather modification via long-term projects aimed at understanding cloud and precipitation microphysics and dynamics, as well as cloud modeling and cloud seeding evaluations are extremely urgent and important. An upcoming national project on weather modification in China will shed light on these issues.

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