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Advances in Weather Modification from 1997 to 2007 in China

GUO Xueliang*[1,2] (郭学良) and ZHENG Guoguang[2] (郑国光)

[1]*Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[2]*Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing* 100081

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ABSTRACT

Rapid and significant advances in issues relevant to weather modification have been made in the last decade in China due to high water resource stresses and severe weather hazards induced by climate change. This paper reported some progress in aspects of theoretical modeling, field experiment and cloud-seeding tools, as well as research projects regarding weather modification during the ten years from 1997 to 2007.

More advanced theoretical models such as cloud models with bin-microphysics and glaciogenic and hygroscopic seeding processes, and mesoscale cloud-resolving models with AgI-seeding processes have been developed to study seeding-induced changes of cloud structure and precipitation as well as to understand critical issues in association with weather modification. More advanced cloud-seeding tools such as mobile ground-based launching system of AgI-rockets and aircraft-based AgI-flares have been developed and used in operation. Several important projects aimed at exploring weather modification techniques and their applications have been conducted during this period.

Key words: advances, weather modification, China

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1. Introduction

Since the pioneering experiments of demonstration on dry ice seeding by Schaefer (1946) and the discovery in the ice nucleating ability of silver iodide by Vonnegut (1947), the modern era of weather modification activities began immediately through field experiments on glaciogenic seeding (dry ice and silver iodide) (Kraus and Squires, 1947). The reason that weather modification operational programs have been increasing in number and scale across the world is mainly due to these facts: First, because weather modification could potentially contribute to alleviating water resource stresses and severe weather hazards; these huge demands have been increasing rapidly with population growth and climate change in the 21st century. Second, human-made atmospheric changes, such as the emission of industrial air pollution that can alter atmospheric processes on scales ranging from local precipitation patterns to global climate, are a reality. These facts push people to make a sustained effort to reduce and mitigate the effects from weather by artificial methods as long as new tools and techniques are available.

In 1958, China conducted its first cloud-seeding experiments in both northern and western China (Cheng, 1959). Nowadays, China has been one of the most active countries in weather modification operation (Fig. 1). The China Meteorological Administration (CMA), Chinese Academy of Sciences (CAS), and several universities have established specific research centers or laboratories on cloud and weather modification. China has been conducting operational services of weather modification by using artillery, rockets containing mixed AgI agents, in over 30 provinces, in which 24 provinces are presently using aircraft with AgI flares to do rain enhancement operations. Almost all weather modification operations are funded by the local government in China. However, the national research projects on weather modification research funded by relevant departments of Chinese Central Government have increased in recent years. From 2000 to 2005, the Ministry of Science and Technology of China (MOST) sponsored a key project: research and demonstration of rain enhancement techniques. National Natural Science Foundation of China (NSFC)

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*Corresponding author: GUO Xueliang, guoxl@mail.iap.ac.cn

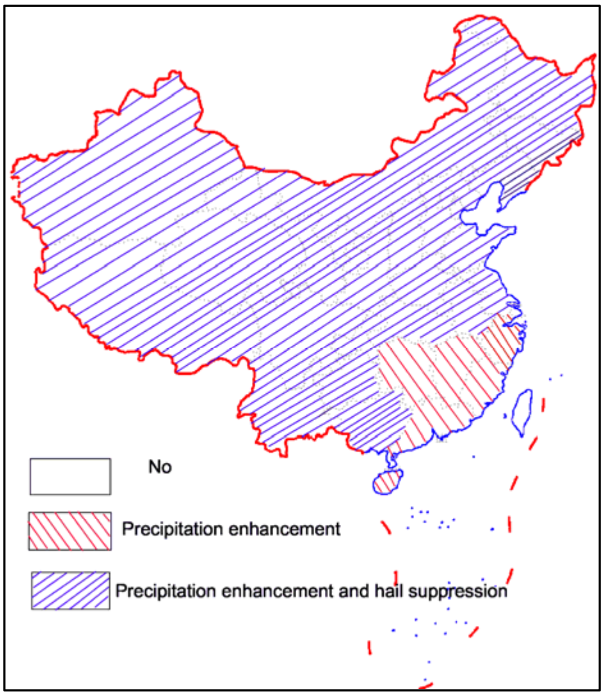

Fig. 1. Sketch map of weather modification operations in China in 2002 (From Zheng et al., 2003).

also supported several key projects on theoretical and experimental research on weather modification. The Chinese Central Government has also started to pay more attention to the developing and applying of weather modification technology in enhancing precipitation and mitigating hail fall in recent years. The projects funded by the central government aim to improve equipment engineering and are oriented to introduce more advanced radar, microwave radiometers and aircraft probes in weather modification operations. These projects, which promote cloud seeding techniques, began in 2006 and are planned till 2010 in China. Over 70% of natural damages are caused by meteorological disasters in which severe drought, flood, hailstorms and fog are more common, and the extreme weather events show an increased trend in intensity and frequency in the continental country in recent years. Undoubtedly, the financial support from central government will greatly benefit the improving of cloud exploration ability and the development of weather modification research, experiments and operations in China. One of the potential influences of the central government's attention and support on weather modification may attract a greater number of young, well-educated, people to this field. It may also help to create a sustained development in this area. Some researchers briefly reviewed the progress and discussed some important issues in cloud physics and weather modification in China (Hu, 2001; 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).

The goal of this paper is to address in more detail the recent advances in weather modification research and operations during 1997–2007 in China, and to focus on the progress in the understanding of key issues based primarily on the aspects of modeling, observation, projects and seeding tools. Section one is an introduction. Section two addresses advances in theoretical and modeling studies on weather modification. The scientific projects and experiments on weather modification will be given in section three, and section four will show advances in observation and seeding tools. Conclusion and discussions will be given in the last section.

2. Advances in theoretical and modeling studies on weather modification

Most of the attempts at weather modification have been aimed at initiating the onset or accelerating/suppressing the rate of cloud physical processes involved in precipitation formation. In nature, the efficient conversion from water vapor into cloud particles can only be induced by enhanced low-level atmospheric convergence and the upward motion of moist air, and this dynamical process is a key process to produce significant amounts of precipitation on the ground. Thus, a thorough and complete understanding of atmospheric dynamics and physics and their interactions involving natural cloud and precipitation formation is essential to conduct effective weather medication operations.

During the past several decades, two basic cloud-seeding techniques were proposed. One is called glaciogenic seeding which aims at creating or enhancing the formation of ice crystals, particularly at the conversion of supercooled water to ice by seeding clouds with the appropriate ice nuclei (e.g., silver iodide) or cooling agent (e.g., dry ice, liquid propane and liquid-CO_2). For this cloud-seeding technique, two general approaches have been developed, one approach is so-called static seeding, which focuses on cloud microphysical processes, and is used to create ice crystal particles and enhance snow and graupel production by increasing the number of ice particles and triggering precipitation processes earlier in the lifetime of the cloud. Another approach is dynamic seeding, which increases the buoyancy of the cloud by converting supercooled liquid drops to ice. The subsequent release of latent heat of fusion increases cloud buoyancy, cloud lifetime, and rain production.

Another cloud-seeding technique is hygroscopic seeding, which focuses on the enhancement of rainfall by seeding clouds with appropriately sized salt particles or droplets, promoting the coalescence process. This method is further broken down into two general approaches. The large hygroscopic particles seeding approach focuses on seeding clouds with large salt particles (e.g., $> 10\ \mu$m) and shortening the condensation growth process, thus providing immediate raindrop embryos to start the coalescence process. The hygroscopic flare seeding approach focuses on broadening the initial drop spectrum during the nucleation process by seeding with larger than natural CCN (0.5 μm to 3 μm dry diameter) to enhance the coalescence process in warm and mixed-phase clouds.

China mainly uses the first cloud-seeding technique to conduct weather modification operations over the past several decades, whereas and the second cloud-seeding technique was only used in research experiments. Due to the suffering of severe damage from hailstorms in most parts of northern China, the operational activities in hail suppression were more popular than that in rain enhancement before 2000. The rapid increase of water resource stress in recent years has promoted development of rain enhancement activities across China, and also aroused theoretical and modeling studies on weather modification. Here, the main progress is introduced in the following several aspects.

2.1 *Improving understanding of dynamical and microphysical effects of glaciogenic seeding*

Many researchers investigated the AgI-seeding effect on cloud dynamics and microphysics by using the cloud model in recent years (e.g., You et al., 2002; Chen et al., 2005; Fang, 2004; Fang et al., 2005a; Fang et al., 2005b; Li et al., 2006a,b; Hong and Zhou, 2006; 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 of cloud dynamics and microphysics.

The seeding material is one of the most important factors to determine effective cloud seeding. Silver iodide and dry ice have been most widely used in field projects and most completely tested in laboratories, yet some aspects of their ice nucleation behavior as well as the interaction mechanism between 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 vertically 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 force. But 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 lack of ice nucleation. Since dry ice pellets 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.

We 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 show that the seeding by liquid CO_2 and AgI at $-15°\text{C}$–$-20°\text{C}$ levels of cloud has almost the same dynamic effect on the simulated clouds (Fig. 2a). 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 temperature of $0°\text{C}$–$-5°\text{C}$ enabled the production of a much stronger dynamic effect and precipitation by forming many new convective cells at low-levels in the later stage of seeded clouds (Fig. 2b). The twin-rotating rings are initially formed at a lower altitude at about 4–6 km above ground level (AGL) in the downstream region near the seeded area (Fig. 3a). Due to the effect of stable upper-levels, the rings move horizontally along the levels of 4–6 km. By 60 min (Fig. 3b), the most prominent feature is that the up- and downdrafts meet at around the 4–6 km level and force the air to move horizontally causing another obvious ring to be formed in the upstream region. This process is favorable to the transition of water vapor to cloud vapor, and also glaciation of supercooled water into ice.

Using the same cloud model with the AgI seeding process, the 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 show that the cloud microphysical variations responding to different seeding methods show large differences. The seeding leads to the decrease of the

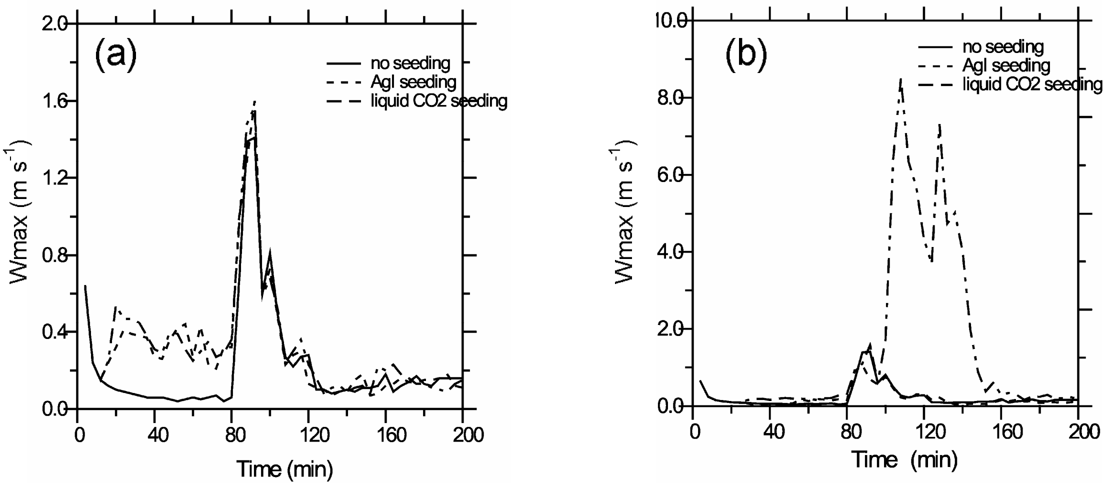

Fig. 2. Comparison of dynamic effect induced from different seeding levels (a) seeded at −15°C−−20°C, and (b) seeded at 0°C−−5°C. From Guo et al. (2006a).

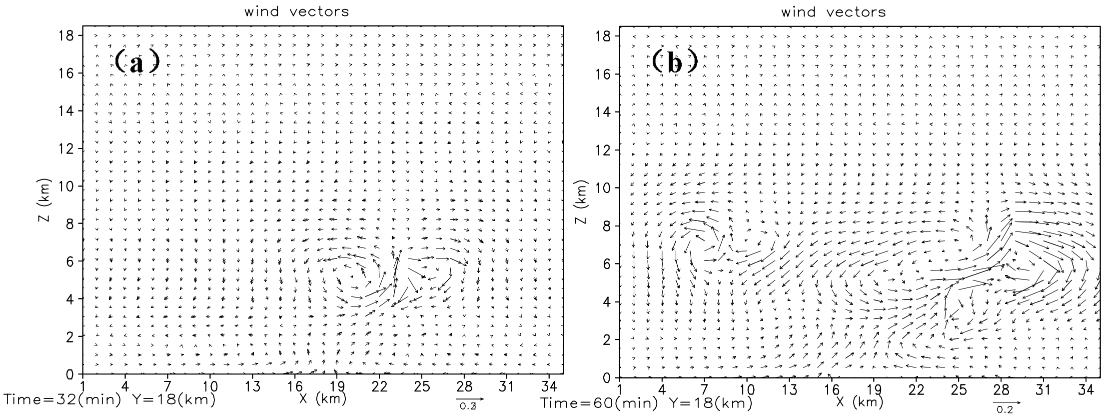

Fig. 3. Twin-rotating wings formed at the lower altitude at about 4–6 km AGL in the downstream region near seeding area induced by liquid-CO_2 seeding. (a) 32 min, and (b) 60 min. From Guo et al. (2006a).

formation of cloud ice, and it enhances snow formation in the cloud developing and maturing stage (Fig. 4a). It was recommended that the cloud seeding conducted in the regions of maximum updraft and supercooled water in the convective cloud may maximize augmentation of surface precipitation (Fig. 4b).

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

2.2 *Advancing understanding hygroscopic seeding technique*

The intention of hygroscopic seeding is to promote the water droplets growth through coalescence, thereby improving the efficiency of the rainfall formation process. Statistical results, observations and modeling results for larger particles (e.g., >10 μm diameter) have provided some statistical evidence (Silverman and Sukarnjanasat, 2000). The field experiments or operations such as the South African and Mexican experiments in which hygroscopic seeding flare was employed have shown the remarkably similar statistical results in terms of the differences in radar estimated rainfall for seeded versus non-seeded groups (Silverman, 2000), and an increase in rain mass 30–60

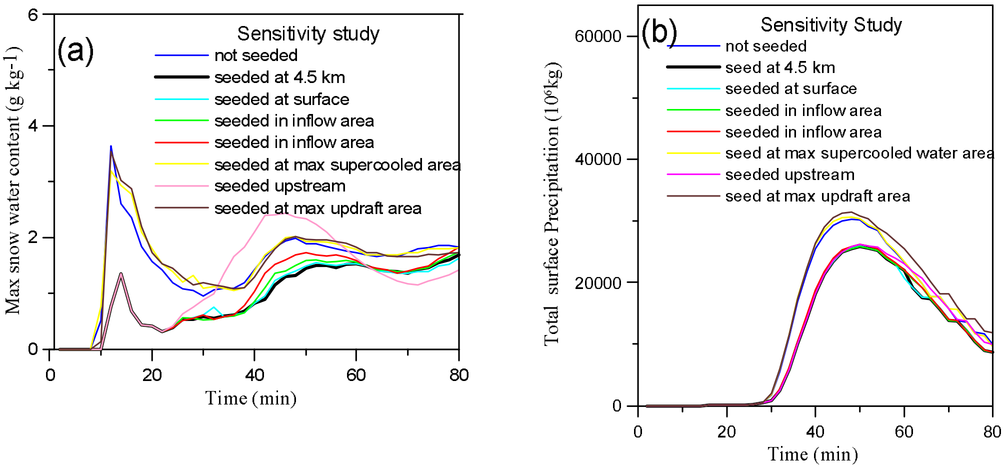

Fig. 4. Time evolution of (a) maximum snow water content and (b) total accumulated precipitation (kg) at the surface for unseeded and different seeded cases. From Guo et al. (2007).

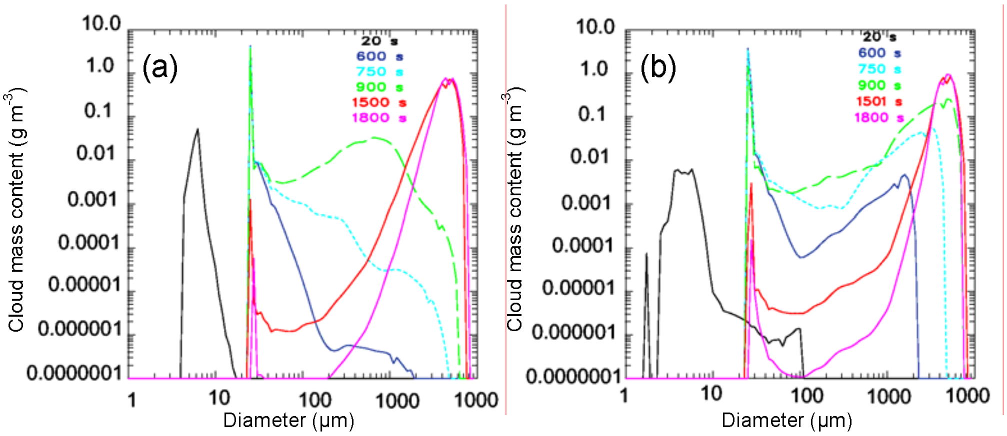

Fig. 5. Effect of hygroscopic flare on cloud spectral (a) non-seeded, (b) seeded.

minutes after seeding was found. A delayed response in radar-derived storm properties was 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). The hygroscopic flare particle 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 effect of hygroscopic flare seeding was studied based on a one-dimensional cloud model; it was shown that seeding can apparently alter cloud spectra and enhance precipitating particle formation (Fig. 5), and the different sized particle seeding has different influences on the formation of drizzle water content under different cloud updrafts (Fig. 6). The results suggested that the hygroscopic particles less than 1 μm

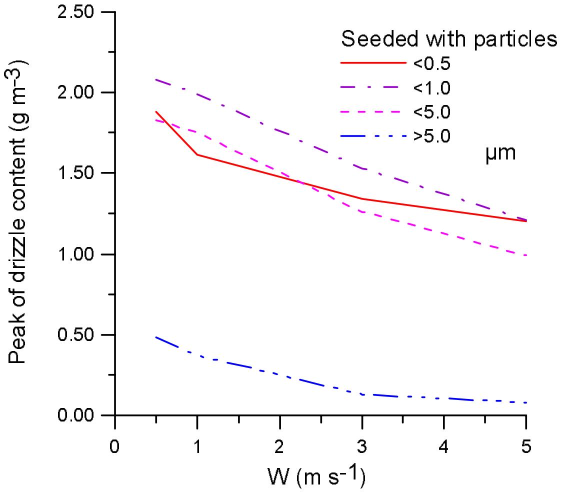

Fig. 6. Effect of different sized particles of hygroscopic flare on cloud water content under different updrafts.

in diameter are the ideal sizes for cloud seeding and particles larger than 5 μm in diameter are too large for relatively weak convective clouds.

2.3 *Insight in hail formation mechanism and application in hail suppression*

The better understanding of hail formation processes such as hail embryo formation, transport, and further growth is essential to conduct effective hail suppression operation. Some researchers investigated hail formation in hailstorms with radar data (e.g., Zhu et al., 2004; Xu et al., 2006a,b).

Numerical models of storms can be a useful tool for understanding hail formation and growth processes. More sophisticated models (e.g., bin-mixed-phase, detailed cloud microphysics and dynamics) are feasible with an increase in computer capacity. Hail-cloud models with hail-parameterized microphysics have been widely used to study hail formation mechanisms and hail-cloud seeding in recent years in China (e.g., Hong, 1998; Hong, 1999; Hong et al., 2002; Wang and Lei, 2002; Xu and Duan, 2001; Xu and Duan, 2002; Zhou et al., 2001; Hu et al., 2003; Zhou et al., 2003; Fu et al., 2003; Fu and Guo, 2007a; Zhu et al., 2004; Sun et al., 2004, Li et al., 2003a,b, 2006a,b; Xiao et al., 2006).

In this so-called hail-parameterized model, hailstones are assumed to be distributed by an inverse exponential size distribution and their growth rates are based on mass weighted mean terminal velocities. The errors caused by these assumptions are particularly large when the size ranges of hydrometeorological types, such as hail, can vary significantly over the spectrum. To overcome this shortcoming, a hail-cloud model with a detailed hail-bin microphysical scheme was developed in China (Guo et al., 2000, 2001a,b; Guo and Huang, 2002). The model can more naturally reflect hail growth process and provide four-dimensional hail information, such as hail number concentration, not available in the previous model, and, more importantly, it can be used in the study of hail suppression in China. The model was used to study hail formation processes in a multicellular hailstorm and found that hailstones can be formed in a recirculation process from the main cell to the daughter cell and can also reenter the main updraft by low-level inflow (Fig. 7). This model is also used to simulate super cellular hailstorms in Japan and China (Guo et al., 1999a,b; Fu et al., 2003; Fu and Guo, 2007a,b; Sun et al., 2004). Kang et al. (2007) used the model to explore the hail formation mechanism in the hailstorm over the Qinghai-Tibetan Plateau. Fang et al. (2002) parameterized the experiment result in the range of Reynolds numbers corresponding to natural hail clouds in 1D and 3D cumulus models to simulate hail growth in different areas of China.

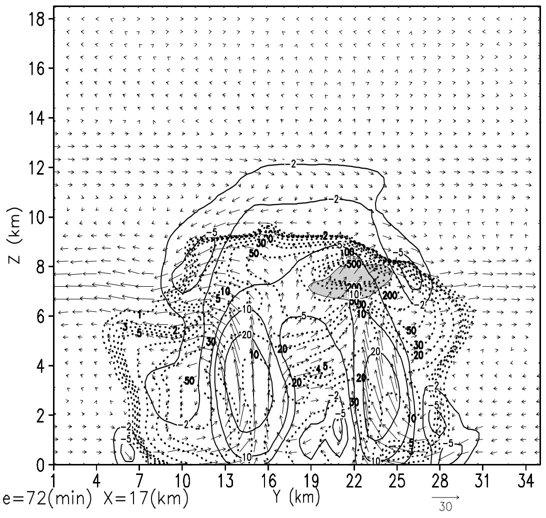

Fig. 7. Hail growth via recirculation process in a simulated multicellular hailstorm. Solid lines are updraft, dotted lines denote small ice particles and the shaded are is high hail formed region. From Guo and Huang (2002).

The application of a hail-cloud model in early identification of hail clouds and seeding methods in hail suppression operations has increased in recent years in China (Xiao et al., 2002; Li et al., 2003b). The nucleation processes of seeding agents of AgI and liquid CO_2 were developed in the hail-bin model (Guo and Fu, 2003) to study seeding effect on hail suppression mechanisms (Guo et al., 2004; Zhou et al., 2005). These studies show that the seeding on hail clouds can significantly suppress hail formation by precipitating more rain and/or precipitating earlier if appropriate seeding methods were used.

Since the hail models described above were usually initialized with a single sounding, they tend to produce a homogenous hail growth background. In order to improve the location, time and amount of hailfall at the surface and provide more information for hail suppression operations, the hail cloud model should be initialized with mesoscale model output. Thus, some researchers (e.g., Guo et al., 2003; Kang et al., 2004a,b) studied hail formation in convective cloud systems by using a hail-bin model initialized with output from MM5 model.

2.4 *Improving understanding of urbanization-induced weather modification and cloud merging process*

The abnormal precipitation distribution and intensity have often been found in big cities such as Beijing

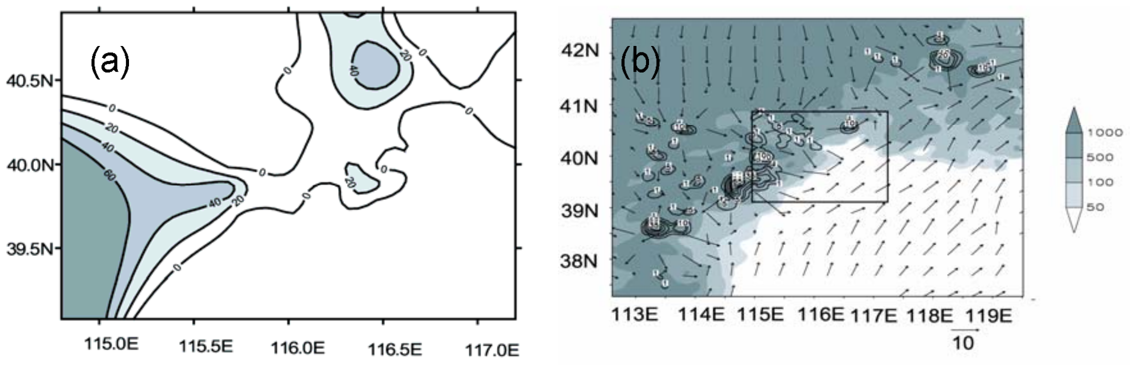

Fig. 8. The distribution of accumulated precipitation (mm) for (a) observation, (b) model simulation in the Beijing region. The wind vectors denote horizontal component of wind at the surface. From Guo et al. (2006b).

and Shanghai, which poses a new challenge in forecasting severe convective systems in the urban regions due to rapid development and urbanization in China. Guo et al. (2006b) studied the effect of urbanization on mesoscale convective systems in the Beijing region by using the MM5 model (Figs. 8a, b). They found that the total precipitation in the urbanized region decreases, and its distribution tends to become concentrated and also intensified along the borderline between urban and non-urban regions. 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 role of the cumulus merger process in the formation of mesoscale convective systems (MCS) has been widely studied in investigations of development and enhancement of the cloud echo area, mixed-phase microphysics, rainfall and cloud-ground lighting activities, and also possible application in weather modification. Fu and Guo (2006, 2007b) investigated the cumulus merging processes in generating the MCS on 23 August 2001 in the Beijing region by using a cloud-resolving mesoscale model of MM5 and found that the merger processes occurred among isolated convective cells, formed in high mountain region during a southerly moving process, play a critical role in forming an MCS and severe precipitating weather events, like hailfall, heavy rain, downburst and high-frequency lightning in the region. The formation of the MCS goes through multiscale merging processes from single-cell scale merging to cloud cluster-scale merging and high core merging. The merger process can apparently alter cloud dynamical and microphysical properties by 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, especially by which, the more graupel-like ice particles are formed in clouds. The explosive convective development and the late peak lightning flash rate can be found during the merging process.

3. Scientific projects and experiments on weather modification

3.1 *National projects*

Several national research projects in terms of weather modification have been conducted in the last several years in China. The national key project: Research and demonstration of rain enhancement techniques sponsored by China MOST and lasted for 5 years from 2001 to 2005 (Zheng and Liu, 2001). This project was the first relatively large and state-supported project on rain enhancement. From this, the intensive exploration studies on cloud structure and cloud seeding via field observation, models and laboratory experiments were made. The young, highly-educated researchers involved in the project made the application of advanced models in weather modification possible.

National Natural Science Foundation of China also funded several key projects on cloud and weather modification from 2004 to 2006. These projects, however, were focused on more fundamental issues such as cloud formation and structure, and weather modification methods.

A project: Research and development of key techniques and instruments of weather modification under National Science and Technology. Supporting Program sponsored by China's MOST has being started in 2006 and will also last for 5 years until 2010. This project coves many attempts at weather modification, such as technologies in warm cloud seeding, warm fog dispel and the development of hygroscopic seeding agents.

Undoubtedly, the weather modification research and operation will be pushed forward substantially under these projects. Other national projects oriented to improve exploration ability in the operation and research of weather modification are also being applied. More advanced technologies such as Doppler radar, millimeter wave radar, polarized radar and microwave radiometers, as well as better aircraft, will be equipped and used in weather modification operation and research through these projects in the near future.

3.2 *Aircraft exploration and investigation of aerosol and cloud structure*

The cloud microphysical processes taking place within a cloud that lead to precipitation are very complex. The number and characteristics of aerosol particles in the cloud-forming air are one of the key factors in determining cloud and precipitation formation. A tremendous amount and wide variety of natural and anthropogenic particulate matter such as soot, sea salt, volcanic ash, wind-blown sand and dust, biogenically-derived materials (e.g., pollens and spores), and a variety of sulfur, nitrogen, and carbon compounds resulting from industrial pollution, biomass burning, and other combustion processes are contained in the atmosphere. Soluble and hydrophilic particles can absorb water and eventually act as CCN. Insoluble particles with wettable surfaces may adsorb water and serve as large cloud drop nuclei or ice nuclei. Insoluble particles that have a crystalline structure may be referred to as ice nuclei (IN) and can provide efficient growth of ice crystals.

Differences in the initial population of atmospheric aerosols affect the cloud particle and cloud drop populations, which subsequently affect the amount of precipitation reaching the ground. The evidence of local to regional cloud and precipitation changes due to anthropogenically induced aerosols is widely documented and has been of great concern in recent years. The aircraft investigation on aerosol size distribution under cloudy and cloud-free condition has been conducted in many regions of China (e.g., Zhou et al., 2004; Zhao et al., 2006; Zhang et al., 2006, 2007; Fan et al., 2007; Qi et al., 2007).

Figure 9 displays 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 and its surrounding area. It shows that under clear conditions there is a strong accumulation zone of haze aerosols near the surface in both days. But the number concentration on 12 September 2004 is much higher than that 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 is primarily due to the effect of dust flow in the upper levels of north-western region.

4. Advancing in observing and seeding tools

Over the past ten years there has been a rapid de-

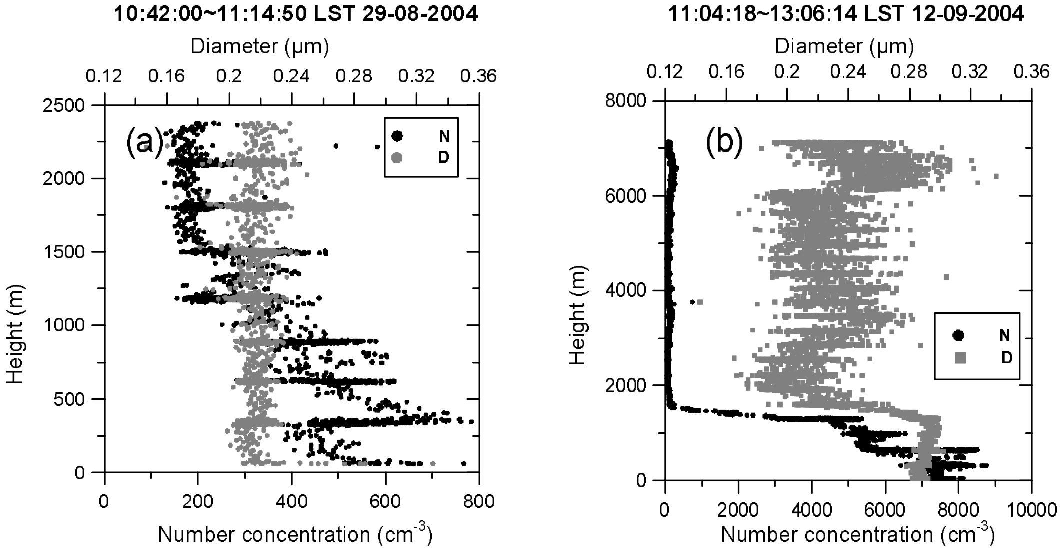

Fig. 9. Vertical distribution of aerosol number concentration (black dot) and diameter (gray rectangle) during ascending flights derived from PCASP: (a) 1042:00 LST–1114:50 LST 29 August 2004; (b) 1104:18 LST–1306:14 LST 12 September 2004. From Fan et al. (2007).

velopment of a multitude of advanced tools in observing and seeding of cloud systems in China. This progress provides an effective way to explore cloud structure, identify seeding targets, and determining effective seeding locations. It is becoming possible to conduct detailed studies on the chain of physical events as well as more definitive assessments of the effects induced by seeding.

4.1 *Application of advanced measurement and observing tools*

One of the greatest advancements in these aspects is that the use of Doppler radar is becoming popular in weather modification operations in China. Multiple Doppler networks are also emerging in some regions of China. Highly mobile ground-based polarization Doppler radar has also been used in weather modification experiments from 2006 (Fig. 10). These capabilities are of great value in identifying the types of particles present and has potential application in assessing cloud-seeding experiments since polarimetric particle classifications derived from this radar can be used in many aspects of weather modification. This includes the ability to reveal the transformation of supercooled liquid water droplets to ice crystals in glaciogenic seeding and the development of large drops in hygroscopic seeding etc. Current polarization radar is only available in the national weather modification project, but will expand rapidly in operation over the next 5 years.

The millimeter-wave cloud radar with a wavelength of 8 mm is also being used in operations, but is not popular at the present time.

Airborne cloud measurements used in weather modification operations have been developed rapidly in China. Several Airborne Particle Measuring system (PMS) together with hot-wire liquid water probes have become the principal tools for characterizing aerosol and cloud particle properties for the last decade. The Passive Cavity Aerosol Probe (PCASP) used for measuring the size distribution of aerosol particles between 0.1 μm and 3 μm in 15 size channels. The Forward Scattering Spectrometer Probe (FSSP-100), or improved version, can measure cloud droplet distributions between 0.5 μm and 47 μm diameter in 15 size bins. The Optical Array Probes (OAPs) were also popularly used to measure the concentration and sizes of precipitating particles as well as two-dimensional images of hydrometeors in China. The more advanced Cloud Aerosol and Precipitation Spectrometer (CAPS), the Precipitation Imaging Probe (PIP) and Cloud Condensation Nuclei Counter, etc., have been successfully installed on one cloud-seeding aircraft in Beijing City in 2007. These instruments provide more detailed information on clouds and help to improve weather modification operations.

The next most popular instruments being used in Chinese weather modification operations are ground-based and airborne microwave radiometers (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 or 23 GHz and 31 GHz, it has more important applications in weather modification. But this instrument is not efficiently used in locating regions of high concentration of supercooled liquid in natural clouds in weather modification operations due to the lack of further validation and improvement of relevant retrieval techniques. Airborne-based microwave radiometers were also developed, but the application and further improvement is still in initial stages. More sophisticated ground-based twelve-channel microwave radiometers with capabilities in observing water vapor, liquid water, temperature, humidity, etc., were used in recent weather modification operations.

Retrieval information suitable for cloud-seeding operations from different satellites and ground-based GPS-network receivers has also experienced rapid progress in recent years.

4.2 *Developing advanced seeding tools*

A relatively rapid advancement in cloud-seeding tools has been seen in last decade. Most of the advanced aircraft equipped with AgI flare agents and mobile AgI-rocket launching system have been widely used in weather modification though the artillery-seeding with AgI-shell and are still used in some regions (Fig. 11). Rockets for weather modification have been developed and can contain 11 g of AgI per rocket.

5. Conclusions and discussions

Over the past decade, there have been considerable advances in issues relevant to weather modification in China due to high water resource stresses and severe weather hazards. For instance, more advanced cloud models with bin microphysics and mesoscale models with glaciogenic and hygroscopic cloud seeding processes have been developed and used in order to understand the variations of cloud microphysics, dynamics and precipitation processes induced by cloud seeding. The new approaches in hail formation mechanisms and possible applications in hail suppression operations have been proposed. Background concentration and sizes of aerosol, the effect of urbanized surfaces on the precipitating system and multiscale cloud merging processes were investigated based on aircraft ex-

Fig. 10. X-band polarization Doppler radar in Institute of Atmospheric Physics, Chinese Academy of Sciences.

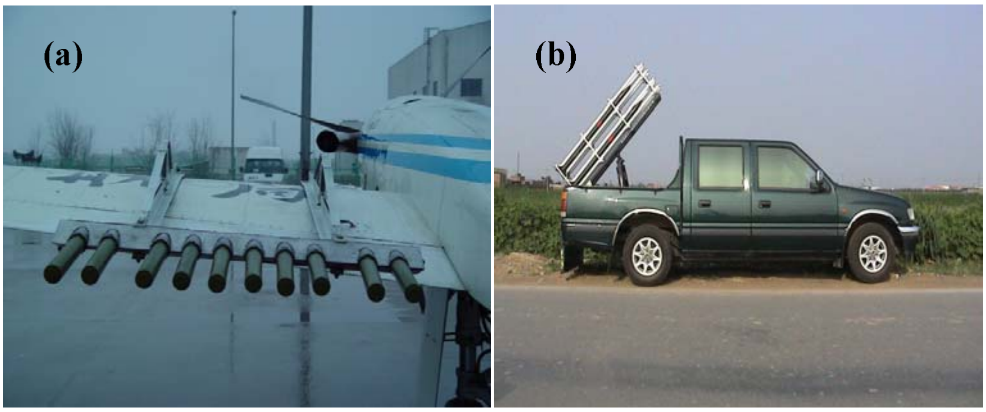

Fig. 11. Seeding tools widely used in current weather modification operation in China, (a) aircraft seeding system equipped with AgI flare agent, (b) mobile AgI-rocket launching system.

ploration and mesoscale cloud-resolving models. More advanced cloud-seeding tools such as mobile ground-based AgI-rocket launching systems and aircraft-based AgI-flares have been developed and used in operation. Several important projects aimed at exploring weather modification techniques and their application sponsored by the Ministry of Science and Technology of China and the National Natural Science Foundation of China been conducted.

Despite significant advances in weather modification research and remarkable advances in observing technology in recent years in China, there are still deficiencies in the ability to exercise a degree of control over the weather.

The main limitations and problems of the current status of weather modification activities in China are primarily shown as:

(1) Lack of scientifically evaluated criteria for seeding operations.

(2) Some advanced technologies have not been efficiently used in seeding planning and justification, operations, and post-operation analysis.

(3) Lack of well-designed observation of cloud and atmospheric background.

(4) The fundamental long-term research relevant to cloud and precipitation formation was not given sufficient attention in the past several years.

The potential for progress in weather modification is dependent upon an improved fundamental understanding of basic and crucial processes of cloud and precipitation in the atmosphere. We may recommend that the sustained effort is made in the following aspects:

(1) Improving cloud model treatment of cloud and precipitation physics, resolution and initialization via observational data and rapid data assimilation techniques.

(2) Applying cloud-resolving model in planning

and justification, operations, and post-operation analysis of weather modification.

(3) Applying advanced observational technologies and accurately retrieving information relevant to weather modification.

(4) Reducing key uncertainties of weather modification by long-term projects aimed at cloud and precipitation microphysics, cloud dynamics, cloud modeling, and cloud seeding.

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