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Recent Progress in Cloud Physics Research in China

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ABSTRACT

A review of China cloud physics research during 2003–2006 is made in this paper. The studies on cloud field experiments and observation, cloud physics and precipitation, including its theoretical applications in hail suppression and artificial rain enhancement, cloud physics and lightning, and clouds and climate change are included. Due primarily to the demand from weather modification activities, the issue of cloud physics and weather modification has been addressed in China with many field experiments and model studies. While cloud physics and weather modification is still an important research field, the interaction between aerosol, cloud and radiation processes, which is the key issue of current climate change research, has become a new research direction in China over the past four years.

Key words: cloud, precipitation, weather modification, aerosols, climate change, China

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1. Introduction

Clouds cover approximately 60% of the Earth's surface. Average global coverage over the oceans is estimated at 65% and over land at 52% (Warren et al., 1986, 1988). Clouds affect the atmosphere by absorbing and reflecting radiation, modifying local air temperature, pressures, and winds, producing precipitation, and mixing and removing gases and particles. In addition to various natural processes, it has been well recognized that human activities may change physical characteristics of clouds in ways other than the traditional methods used in weather modification (Twomey, 1974, 1977; Albrecht, 1989; IPCC, 1995; Ramanathan et al., 2001). A recent study has shown that the precipitation in East-central China was significantly lower during the last 40 years and this reduction of precipitation is strongly correlated to the high concentrations of aerosols (Zhao et al., 2006a). However, our understanding of detailed processes involved in the aerosol's effects on the formation of clouds and precipitation is still limited, and much research in multi-disciplines is being done around the world to improve this situation.

The rapid progress in studies on cloud physics has been made in recent years in China due primarily to the demand from weather modification operations. The more sophisticated cloud models that include two-momentum, size-categorized microphysical scheme and aerosol processes, and advanced observational instrumentation, such as Doppler radar, polarized radar, airborne microwave radiometer, particle measuring system (PMS), and Global Position System (GPS) mesonet, have been used in cloud physics studies. These studies focused on cloud physical processes ranging from convective cloud scale to mesoscale cloud systems. Several projects directed toward cloud physics and weather modification, and air quality pollution, clouds and climate change have been conducted with funds from the Ministry of Science and Technology (MOST) and the Natural Science Foundation of China (NSFC). The threats from long-term drought, severe weather and air pollution pose new challenges in cloud physics research.

Huang et al. (2003) reviewed the advance of research on cloud, fog, precipitation, and weather mod-

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ification at the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP/CAS) in the half century before 2003. Fang et al. (2003) and Guo et al. (2003) gave overviews of hail suppression projects and hail-cloud modeling activities in China, respectively. An introduction of progress in precipitation enhancement in China was made by Wu (2005), with a focus on operational conditions, efficiency evaluation, and practical management. Yao (2006) reviewed weather modification research at the Chinese Academy of Meteorological Sciences (CAMS) over the last 40 years. In this paper, we give an overview of the studies on cloud physics in China over the last four years, from 2003 to 2006. Some previous studies, especially in 2002, are also citied for the continuity. The contents of this paper include cloud field experiments and observation (section 2), cloud physics and precipitation (section 3), cloud physics and hail suppression (section 4), cloud physics and artificial rain enhancement (section 5), cloud physics and lightning (section 6), and clouds and climate change (section 7). Conclusions and remarks are presented in section 8.

2. Cloud field experiments and observation

2.1 *Aircraft measurements*

The airborne PMS (Particle Measuring System) is a set of microphysical instruments that have been widely used in the world since the late 1970s. IAP/CAS and CAMS introduced and implemented the new-generation PMS (Liu et al., 2003f, 2005b), respectively, which have been used for the weather modification field experiments in several provinces of China. Although the PMS is used primarily in the studies of weather modification, it provides invaluable data for the theory studies of cloud microphysics, and in particular, for comparisons with cloud model simulations.

The measurements on cloud microphysical properties with airborne PMS were generally made in the North parts of China during springtime, and the results have been reported in several papers (Li et al., 2003c; Liu et al., 2003f, 2005b; Su et al., 2003a,b; Wang and Lei, 2003; Wang et al., 2005; Yang et al., 2005; Jin et al., 2006; Li, 2006). According to the measurements made in Qinghai Province of Northwest China by Su et al. (2003a,b), liquid water content is low at the stage of cloud development, and high at the stage of precipitating mature cloud. As summarized in Huang et al. (2005), droplet number concentration, liquid water content, and mean diameter of stratiform clouds in the northern part of China are 10–200 cm^{-3}, 0.01–0.1 g m^{-3}, and 7–15 μm, respectively.

The evolution of cloud hydrometeor spectrum and precipitation are the most important processes in cloud physics. Understanding and the adequate modeling of such processes are essential for cloud research on scales ranging from micro-meter to thousands of kilometers. The observed cloud particle spectra were fitted using an N-order Γ-type function for stratocumulus (S_c) and altostratus (A_s) clouds by Li et al. (2003c), and Wang et al. (2005) developed a different distribution function to represent the water drop size distribution in the warm layer of stratus (S_t) clouds in Yan'an of Shaanxi Province of West China. On the other hand, the case study of Su et al. (2003a,b) showed that the cloud droplet spectra is discontinuous at the stage of cloud development, and becomes wider with an order increase of number concentration at the stage of mature cloud. Yang et al. (2005) found the inhomogeneity of stratiform clouds in returning processes based on the analysis of PMS data. They showed that when the aircraft flies into stronger precipitating cloud bands, the mean diameter and particle concentration leap up, and the spectrum width becomes wider. However, microphysical mechanisms behind these variations in cloud drop spectrum were not addressed, and aerosol spectrum observed by the Passive Cavity Aerosol Spectrometer Probe (PCASP), which plays an important role in the activation of aerosol particles into clouds, was rarely reported.

In addition to PMS probes, other instruments were installed in the aircraft for different studies. An Airborne Upward-Looking Microwave Radiometer was developed and used for the measurement of vertically-integrated cloud liquid water content during the operation of precipitation-enhancement in Jilin Province of Northeast China (Lei et al., 2003; Jin et al., 2004). The integrated supercooled cloud liquid water content was found to be great for convective cells inlaid in sheet clouds, with magnitude levels up to 10^3 g m^{-2}.

2.2 *Retrieval from radar reflectivity*

The total amount of water in the atmosphere, in particular liquid water content in clouds, is one of the important factors that determine precipitation process and needs consideration in artificial rain enhancement. In addition to aircraft measurements, remote sensing from the ground appears to be more economic and efficient for the long-term observations. The radar echo has been used in many studies (e.g., Li et al., 2003a; Zhao et al., 2003; Fang, 2004; Xiao et al., 2004; Tian et al., 2005) for cloud microphysical structure analysis and model evaluation. Lü et al. (2003) reviewed the progress in atmospheric remote sensing and satellite meteorology in China, in particular within the Institute of Atmospheric Physics. Liu and Ge (2006) gave an overview on radar meteorology research at the Chinese Academy of Meteorological Sciences over the past half century, focusing on the application of the advanced dual linear polarization radar they developed in watching, warning, and nowcasting of heavy rain fall (Liu et al., 2002, 2005c; Cao and Liu, 2006; Cao et al., 2006). Chen (2002) proposed a concept that can determine the cloud liquid water path from cloud microwave attenuation along the satellite-earth path. Li et al. (2004b,c) developed a method of retrieving cloud water mixing ratio ($q_{\rm c}$), rainwater mixing ratio ($q_{\rm r}$), and water vapor mixing ratio ($q_{\rm v}$) from Doppler weather radar's reflectivity. They showed that the initial fields of the mesoscale numerical model, including these retrieved cloud microphysical messages, would be helpful for numerical nowcasting of the precipitation. Wang and Chu (2002) made an introduction of the successful application of polarization weather radar abroad, and discussed the application problem of polarization weather radar in weather modification. Liu et al. (2003e) reported their progress in developing a polarization lidar for measuring profiles of depolarization ratio of cirrus clouds and Asian dust aerosols. The primary observational results over Hefei, in Anhui Province of East-central China, show that the depolarization ratio for cirrus clouds varies from 0.4 to 0.5. Liu et al. (2006) introduced a method of ground-based microwave radiometer remote sensing retrieval of integrated water vapor and cloud liquid water in the atmosphere. However, bias of the retrieved results is still large, and more work on comparisons between radar retrieval and aircraft measurements should be done.

2.3 *Satellite observation*

There have been increasing studies and usage of satellite data focusing on both macro- and microphysical characteristics of clouds during the last four years in China. Images of satellite, such as National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR), were used to analyze the cloud features of regional hail processes (Zhang and Jin, 2003; Zhang et al., 2004a,b,c). The water content, cloud top temperature, and cloud cover were obtained and used to discriminate hail clouds and choose the best time and area for precipitation enhancement. The effect of a precipitation enhancement operation with silver iodide (AgI) using the aircraft over Shaanxi Province of West China was viewed by NOAA-14 satellite (Yu et al., 2005). A vivid zigzag cloud track was demonstrated on the satellite image, and it was also well simulated with a three-dimensional numerical model of transport and diffusion of seeding material (Yu et al., 2005; Dai et al., 2006).

The passive remote sensing data from the TRMM (Tropical Rainfall Measuring Mission) Microwave Imager (TMI) were applied to retrieve cloud liquid water by Yao et al. (2003). Since the vertical polarization channel of TMI 85.5 GHz they applied is very sensitive to precipitation as well, the method that Yao et al. (2003) have developed cannot be used for retrieving cloud water of precipitating clouds. Liu et al. (2003d) indicated that the channel of 6.9 GHz on the satellite-borne radiometer can be used to estimate column liquid water content of precipitating clouds. Wang et al. (2006a) developed a joint retrieval algorithm for retrieving cloud water of non-precipitating clouds by using the microwave brightness temperature measured at the horizontal polarization channels of TMI 37.0 GHz and 85.5 GHz. They showed that their algorithm can be applied to the precipating clouds in a qualitative sense as well. TRMM remote sensing data were also used to study the three-dimensional structure of rainfall rates and hydrometeors in Typhoon precipitation cloud systems (He et al., 2006; Zhong et al., 2006).

Using the reflection measured by the MODerate-resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua satellites at the channels of 0.65 μm and 2.1 μm, Zhang et al. (2006c) retrieved cloud optical thickness, efficient radius, and liquid water content over the Qilian Mountains of the Tibetan Plateau for the period between 2002 and 2005. They also did correlation analyses between these three parameters and 6 h precipitation over the Qilian Mountains. Their analytical results provide important information for further research on the water resource usage in West China.

Chinese meteorological satellite FY-1C was successfully launched on 10 May 1999. There are ten spectral channels in FY-1C, some of which such as channel 1 (0.58–0.68 μm), channel 4 (10.3–11.3 μm), and channel 6 (1.58–1.64 μm) can be used for cloud particle phase detection. A case study by Liu et al. (2003a) showed that 1.6 μm channel could be used to analyze the thermodynamic phase of cloud particles. Much more work is needed for the retrieval of cloud microphysical parameters with Chinese satellite data.

2.4 *Video images*

The Precipitation Particle Image Sensor (PPIS) was used to directly observe the cloud microphysical structures vertically from the base to the top of the cloud during the heaviest rainfall of the mei-yu front in June 1999 (Wang and Yang, 2003). PPIS is a balloon-borne video-sounder developed by Takahashi et al. (1995), from which images of precipitation particles larger than 0.5 mm are recorded by a camera. In addition to the particle images, the PPIS records the electric charge on the particles and the ambient temperature, humidity, and pressure. The vertical distributions of various cloud particle sizes, number density, and mass density were retrieved from the observations by Wang and Yang (2003). Their analyses showed that ice crystals, graupel, snowflakes and frozen droplets often coexist with the liquid phase in the convective cloud clusters in mei-yu front rainband. The interactions of these particles play important roles in the formation and evolution of rainfall.

3. Cloud physics and precipitation

3.1 *Model development and application*

3.1.1 *Cloud microphysical models*

Numerical simulations play an important role in the studies of cloud microphysical process, precipitation mechanism, and weather modification evaluation. Although many model studies have been reported in China during the last four years, most of these were merely of models' application without fundamental changes in cloud microphysical processes in the model itself. The models used include:

(1) CAMS (Chinese Academy of Meteorological Sciences) models: the 1-D stratiform cloud model (Liu et al., 2005a), which was originally developed by Hu and Yan (1986), and the 1-D time-dependent convective cloud model (Zhao et al., 2003) and 3-D convective cloud model (Li et al., 2003a, 2006c; Fang, 2004; Fang et al., 2005a,b; Liu et al., 2005a), which was originally developed from the microphysical cloud model of Hu and He (1987); (2) SGBH model of Beijing Institute of Applied Meteorology: the 2-D cloud model with a microphysical scheme of size categories of hydrometeor particles (Zhao et al., 2004), which was originally developed by Xu and Wang (1990) and Xu and Duan (1999); (3) IAP (Institute of Atmospheric Physics, Chinese Academy of Sciences) models: the 1-D stratus cloud model (Hong and Zhou, 2005; Wang et al., 2006b), which was simplified from the 2-D microphysical cloud model of Hong (1996), and the 3-D hailstorm model (Xiao et al., 2002, 2006; Hu et al., 2003; Li et al., 2003b; Zhou et al., 2003, 2005a; Kang et al., 2004a,b; Li and Hong, 2005; Chen et al., 2005; Guo et al., 2006b; Yu et al., 2006) and rainstorm model (Xiao et al., 2004), which was improved from a 3-D convective cloud model developed by Kong et al. (1990), Hong (1998), and Guo and Huang (2002). Both two-momentum and bin cloud microphysics were used in these models.

3.1.2 *Cloud schemes in the mesoscale model*

The moisture processes are very important for precipitation, atmospheric general circulation, atmospheric chemistry and climate, and they cannot be ignored in a mesoscale model. Lou et al. (2003) presented a review of the convective parameterization and explicit cloud schemes used in mesoscale models, such as HALF (High Resolution Limited Area Operational Forecasting Model) and MM5 (Fifth Generation Mesolscale Model). Ping et al. (2003) developed and improved the features of the Gregory cumulus parameterization scheme used in the British Weather Office according to the characteristics of area precipitation over China. They showed that the model with improved Gregory scheme can well simulate the precipitation over China.

Liu et al. (2003b, c) implemented three sets of explicit prognostic cloud schemes (two-moment warm cloud, simple mixed-phased cloud and two-moment complicated mixed-phased cloud schemes) into the dynamic framework of the limited-area numerical weather prediction model HLAFS of the National Meteorological Center. According to their simulation results, the mesoscale model including explicit schemes is able to reveal the cloud field evolution and cloud physical characteristics during heavy rainfall development. Zhao et al. (2005b) developed a double-moment microphysical scheme based on the Reisner explicit cloud scheme in MM5. In their new scheme, the number concentration of activated cloud condensation nuclei (CCN) is described with the hypergeometric function and the more reasonable gamma law is used as the basic function for the hydrometeor drop-size distribution. The numerical simulations suggested that the new scheme could provide some valuable information on macro- and micro-structure characteristic of stratus cloud.

3.1.3 *Aerosol-cloud-radiation coupled model*

The first known work on the development and application of the size-resolved aerosol model in China had been carried out by Zhao et al. (1998). This mutil-component size-resolving aerosol model was used to investigate the impacts of nss-sulfate and sea-salt on marine cloud microphysical properties (Zhao et al., 2005a). According to the numerical results of Zhao et al. (2005c), soluble organic components will decrease maximum supersaturation, leading to a decrease of cloud drops activated in the case of a high nss-sulfate and a high updraft velocity. Sea-salt will increase cloud optical depth (COD) in case of low nss-sulfate but will decrease COD when nss-sulfate concentration is high.

3.2 *Cloud microphysics and precipitation mechanism*

3.2.1 *Stratiform cloud*

The comprehensive field experiments showed that the precipitation microphysical process of stratiform clouds in North China observes basically the "seeder-feeder" mechanism (You et al., 2002a). Su et al. (2003a) found the layer-separating phenomenon in the development stage of precipitating clouds by aircraft measurements in Qinghai Province of West China. The frontal precipitation cloud system is an important seeding object for artificial precipitation and generally has the typical structure of "seeder-feeder" cloud.

Using the same 1-D stratiform cloud model of IAP, Hong and Zhou (2005) and Wang et al. (2006b) studied independently the microphysical structure and processes of precipitation formation in cold frontal precipitation stratus cloud systems occurring on 4–5 April 2002 in Henan Province of East-central China. Both studies showed that the cold cloud processes play an important role in rainfall, and the growth of ice particles in the mixed ice water layer and melting of graupel into rain water when falling through the warm zone are very important for precipitation formation. Wang et al. (2006b) showed that ice-phase particles are the main components in the cold clouds both pre- and post-front. According to Hong and Zhou (2005), the ice cloud (seeder cloud), mixed ice water layer, and liquid water layer made a contribution to rainfall by 25.5%, 31.3%, and 43.1%, respectively, and the contribution of the last two (feeder cloud) is about 74.4%. Wang et al. (2006b) argued that almost all of rainwater may come from graupel melting, and the mechanism of cold front precipitation could mainly be described as "vapor-snow-graupel-rain water".

Li et al. (2006a) further studied the macro- and micro-structures and precipitation mechanism of the cold-frontal cloud of 4–5 April 2002 in Henan Province of East-central China using the MM5 model with the combined Reisner cloud scheme included. For the same case, the different precipitation mechanism was proposed by Li et al. (2006a). They argued that the cold- and warm-cloud processes coexist in the area and that plentiful amounts of cloud water initially are produced by warm-cloud process at both the low and middle levels. Their analyses showed that after being generated at the upper level, ice crystals are mostly converted into snowflakes and less graupel, and the melting of these ice particles, especially mass snowflakes, contributes to the most of surface precipitation.

3.2.2 *Convective cloud*

The upper reaches of the Yellow River are located in the east of the Tibetan Plateau with much water vapor resource and frequent rainfall. Zhao et al. (2003, 2004) studied the precipitation mechanism of shallow convective clouds in the upper reaches of the Yellow River. They analyzed radar echo data, surface observation data, and rain particle spectrum data over the upper reaches area of the Yellow River from June to September 1997–2000, and found that in summer all clouds are mixed-phase with a thick layer of warm cloud at the bottom of the layer. Through the case study of rain particle spectrum evolution, Zhao et al. (2003) preliminarily inferred that both warm rain and cold rain formation mechanisms exist in the microphysical processes of rainfall, but the warm rain mechanism plays an important part in the precipitation development of clouds. Zhao et al. (2004) further simulated microphysical characteristics of convective cloud precipitation using a 2-D size-resolved cloud model, SGBH, and argued that the formation mechanism of warm rain in the shallow convective cloud may play a very important role in the development of convective precipitation.

The results of Zhao et al. (2003, 2004) seemed to be in disagreement with the pervious study of Wang et al. (2002). Through numerical simulation of the characteristics of convective cloud with a 3-D fully elastic cloud model of IAP, the latter indicated that the main process of convective cloud in the upper reaches of the Yellow River is cold, and most of the precipitation are graupel and frozen droplets. But it should be noted that the conclusions given by Zhao et al. (2004) are for shallow convective cloud. On the basis of observational data and the CAMS 3-D convective cloud model simulations, Fang (2004) showed that the precipitation of convective cloud in Qinghai Province of West China is mainly determined by cold cloud rain processes. She also demonstrated that graupel play an important role in precipitation and their formation is closely related to ice crystals. Li et al. (2006b) analyzed the raindrop-size distribution in the Maqu region of Gansu Province of West China. They argued that the warm rain process can make a contribution to precipitation although cold rain process is the main precipitation mechanism over the Tibetan Plateau.

It is noted that although the models used could reproduce convective cloud structure, only radar echo and rain droplet spectrum data, instead of observational cloud microphysical parameters, were used for model comparisons in these studies.

3.3 *Cloud physical processes and heavy rainfall*

The mesoscale models with explicit cloud schemes have been used to study the effects of cloud physical processes on heavy rainfall, in particular mei-yu front rainfall (Kang et al., 2003; Liu et al., 2003c; Sun and Wang, 2003; Wang and Yang, 2003; Yang et al., 2003; Zhou et al., 2005b, 2006). The cloud-top temperature of black body (TBB) observed from the satellite was generally used to compare with the cloud-top temperature simulated by the model. The outline, location, strength, scale, formation and dissipation, and direction of movement of a cloud system were generally simulated better with the explicit cloud microphysical schemes, such as the Reisner scheme. It was concluded that ice-phase cloud microphysics processes have significant effects on mesoscale processes and their thermal and dynamical structure, especially for precipitation production and maintenance of heavy rainfall during its early developing stage.

Wang and Yang (2003) investigated the cloud microphysical structures for the heaviest rainfall during the mei-yu front in June 1999 by analyzing both the observational data obtained using the balloon-borne Precipitation Particle Image Sensor and the model results simulated using the MM5 with the Reisner graupel explicit moisture scheme. According to their analysis, the mixed-phase cloud process, in which the ice phase coexists and interacts with cloud and liquid phase (cloud and rain drops), plays the most important role in the formation and development of heavy convective rainfall in the mei-yu front system.

Using a 3-D severe convective rainstorm model of IAP, Xiao et al. (2004) studied the torrential rainstorm occurring in Wuhan of Hubei Province of South China on 21 July 1998. They showed that the warm-cloud process was the main developing process in the rain formation of this event. But they also pointed out that the ice-phase microphysical processes can greatly speed the rain formation with the graupel particles contributing the highest to the melting ice-phase particles.

The change of cloud droplet spectra can modify the microphysics and radiative processes of the atmosphere, which in turn affects surface precipitation. Zhou et al. (2005b,c) studied the impact of cloud droplet spectral change (CDSC) on mesoscale precipitation for the two cases, a South China storm on 8 June 1998, and a Yangtze River storm on 22 July 2002, by employing the MM5v3 with newly developed, dual-parameterized CAMS explicit moisture scheme coupled. According to their results, CDSC has only a slight influence on the rainfall distribution pattern, but can significantly change the precipitation intensity, especially the position and intensity of the precipitation centers.

3.4 *Effect of urbanization on the mesoscale convective system*

Rapid development of urbanization in China poses a new challenge in forecasting severe mesoscale convective system in the urban regions. Guo and Fu (2003) and Guo et al. (2006a) studied the effect of urbanization on mesoscale convective systems in the Beijing region by using MM5. They found that the upper convection weakens and the lower convection strengthens, due primarily to the increase of surface roughness over land that enhances the lower convergence. They also showed that the total accumulated precipitation in the whole domain decreases, especially in the urbanized region, and its distribution tends to become concentrated and also intensified along the borderline between urban and non-urban regions. The simulated precipitation intensity and distribution with the urbanization effect included are more consistent with those observed in this region.

4. Cloud physics and hail suppression

4.1 *Formation mechanism of hail clouds*

With a 3-D parameterized hail cloud model of IAP, Hu et al. (2003) demonstrated that most of the hailstorms in the Xunyi County of Shaanxi Province of West China have an accumulation zone for supercooled raindrops, which is the area where most hail embryos form mainly from frozen drops. Kang et al. (2004b) simulated the formation and growth of hailstorms over the central part of Gansu Province of West China, which is located in the northeast of the Tibetan Plateau, using the hail cloud model with hail-bin microphysics. They showed that mesoscale humidity and dynamics are important factors that determine hailstorm intensity and hail size. By adding snow as a new kind of hydrometeor, Li et al. (2003a) improved the CAMS 3-D convective cloud model. The structure of hail clouds during a hailstone case in Beijing in 1996 was well simulated with the improved model.

The mechanism of cave channels (CC) had been proposed by Xu and Duan (2001, 2002). With the numerical simulation of hailstorm and hailstone growth, they found that there exist a core of main-updraft (MUD) and a zero-area for the horizontal wind speed relative to the hailstorm. They also showed that in the vertical section there is a zero-line from the edge to the core of MUD, below which the wind blows towards the core and upon which the wind blows away. The cave channel with a volume of about 6% or smaller of the total of hailstorm, is just located close to the core of MUD and below the zero area. Once the particles enter CC, they cannot escape its attraction, just like a trap, until they become large stones and fall down from the exit-end. Kang et al. (2004a) showed that the formation and growth of hail on the northern border of the Tibetan Plateau observed the CC mechanism. In addition to the zero-line region, they found another high water content region for small ice particles (with diameter smaller than one millimeter, i.e., $D < 1$ mm), graupel and hail embryos (1 mm$< D <$ 5 mm), and small hailstones (5 mm$< D <$ 10 mm) over −30°C to −50°C levels of cloud at the initial stage of hail formation. It was revealed that the CC is the effective region for the formation and growth of hail. Tian et al. (2005) further verified the CC mechanism by the Doppler radar observations and the analysis of some reliable previous work. They showed that the existence of CC in hail clouds depends on the interaction between the stream and hydrometeor field. One end of the CC connects with the embryo formation area, and the other with large stone formation area. While moving around the zero line of horizontal wind, particles concentrate and accumulate at the CC. Zhu et al. (2004) analyzed the structure of three hailstorms based on a series of the radar scan data. They pointed out that the "cave channel" might exist at the middle-up level of the "S" shape intense reflectivity area that had formed within the anticyclone in the storms.

The heat and mass transfers play a critical role during the hail growth. Zheng (1994) had proposed a parameterization of measured heat transfer coefficients under Reynolds numbers that are related more closely to actual hail scales. Fang et al. (2005b) applied this parameterization to the CAMS 1-D and 3-D hail cloud models. It was indicated that the simulated melting rate, evaporation rate, and dry-wet growth rate of a hailstone increase by 12%–50%, 10%–200%, and 10%–40%, respectively, with the improved models with respect to the prototype models.

4.2 *Hail suppression*

Seeding tools of AgI-containing artillery shells and rockets are widely used in hail suppression at present in China, but systematic studies on their efficiency are lacking. On the basis of the theory of liquid water accumulation for hail-formation and growth, Zhou et al. (2003) and Li et al. (2003b) studied the effects of AgI seeding in Henan Province and Shaanxi Province, respectively, using the IAP 3-D hail cloud model. The influences of seeding time, height, and other conditions were investigated through numerical experiments. These results are expected to give some guidance for the improvement of the seeding efficiencies in practice.

The mechanism of CC provides one of the scientific bases for hail suppression. Kang et al. (2004b) pointed out that the region of formation and growth of hail in hail clouds is in agreement with the intersection of upward air flow and downward air flow, which is the main region to put hail embryos for hail suppression. Tian et al. (2005) further suggested that the target area should include the CC, which locates at the flank of the main updraft and immediately below the zero line of horizontal wind.

The dynamical effects on precipitation formation of hailstorms were studied by Zhou et al. (2005a) by means of introducing artificial updraft restraint in the IAP 3-D convective storm numerical model. The results indicated that at the earlier stage of the development of a hailstorm, an artificial restraint with a common intensity (4 m s^{-1} reduction of vertical velocity in 5 min) can highly influence the development and precipitation of the hailstorm and increase its surface precipitation, especially the amount of hail fall. However, in the later stage of the hailstorm development, the restraint has only a small influence on the precipitation.

Li and Hong (2005) improved the IAP 3D hail cloud numerical seeding model by treating the seeding ice crystal as a separate predicted parameter in the equations. The mechanism of hail suppression they proposed is that a number of seeding ice crystals are produced by seeding, so that graupel and frozen drops increase quantitatively, and so do the amount of hailstones from convertsion of graupel and frozen drops. Thus, hailtone size decreases and, as a result, the intensity of hail fall and the kinetic energy flux of hailstones decrease.

5. Cloud physics and artificial rain enhancement

Studies on cloud microphysics and precipitation, which are closely related to artificial precipitation, have been introduced in section 3 and will not be repeated in this section.

5.1 *Theory and model simulations*

During the dry seasons of spring and autumn in the North China, cold stratus clouds are the main precipitation cloud and thus the object of artificial rain enhancement. It is known that supersaturated water vapor with respect to ice can be converted into precipitation after ice seeding besides supercooled water, and the release of sublimation latent heat can lead to the increase of temperature and updraft in the seeded cloud regions and promote the development of cloud precipitation (Hu, 2001). Hong and Zhou (2005, 2006) argued that the "seeder-feeder" cloud system is an important structure for artificial precipitation. In addition to cloud structure in the cloud system, the precipitation mechanism, amount of supersaturated water vapor with respect to ice, thickness of cloud water, supercooled water content, ice concentration, and precipitation efficiency (precipitation efficiency of condensation water and sublimation water) are also important conditions for artificial precipitation, which should be considered in an integrated way for qualitative assessment of seeding potential. Mao and Zheng (2006) emphasized the importance of the lifting movement, which induces cloud formation, and the water vapor content in the lifting air mass for the choice of the cloud seeding location and timing in weather modification. They argued that in addition to the microphysical conditions, measurements of the lifting movement and the water vapor in the lifting air mass should be greatly strengthened as well.

The natural cloud development processes in Qinghai Province of West China were studied with the CAMS 3-D cloud model (Fang, 2004; Fang et al., 2005a; Li et al., 2006c). Li et al. (2006c) indicated that convective precipitation is almost all transformed by melting of graupel, but in unseeded clouds, the ice crystal amount is so rare that it contributes little to graupel formation. After seeding, the transformation from ice crystals to graupel is enhanced. Fang (2004) and Fang et al. (2005a) suggested that AgI seeding should be done before ice nucleus largely activate, so that rain enhancement could be improved by increasing ice crystals and decreasing supercooled water. Chen et al. (2005) simulated an event of cold vortex precipitation and hail in Liaoning Province of Northeast China with the IAP 3-D convective cloud model and showed that the ice particles melting, especially graupel melting, play the main role in cloud and precipitation formation. They argued that the optimal time of AgI-seeding should be at the mature cloud stage and the convective-stratiform mixed clouds have considerable seeding potential to enhance precipitation.

In 1995, De Mott (1995) published their dynamic chamber experiment results, in which they identified and quantified the effect of the four ice-forming mechanisms by AgI, i.e., deposition, contact freezing, condensation, and immersion freezing. Liu et al. (2005a) applied the experiment results of De Mott (1995) to the box model, the 1-D stratiform cloud model, and the 3-D convective model of CAMS. They showed that humidity, temperature, cloud droplet concentration and the cloud holding time are the main influence factors in AgI nucleating process.

The quasi-precipitation efficiency is defined as the ratio of precipitable water to the total water resource in the atmosphere over the region (Li et al., 2006a). Li et al. (2006a) studied a cold-frontal cloud in Henan Province of East-central China on 4–5 April 2002, and showed that most of the precipitation is yielded along the cold-frontal line. They estimated that only 23.1% of the total water vapor in the simulated area is converted into surface precipitation, which means that most water vapor entering the studied region is not effectively converted into surface precipitation. Thus, the cold-frontal clouds imply a very high seeding potential for precipitation enhancement.

Guo et al. (2006b) compared dynamic and microphysical effects of cloud seeding by AgI and liquid carbon dioxide (liquid CO_2) using the IAP 3-D cloud model initialized with the rawinsonde sounding taken from the Pinliang station located in West China. The model results showed that the seeding by liquid CO_2 and AgI at $-15°C$ to $-20°C$ levels of cloud has almost the same dynamic effect on the simulated clouds. However, the initial seeding conducted by liquid CO_2 in the region of maximum supercooled water with temperatures of 0 to $-5°C$ are able to produce a much stronger dynamic effect and precipitation by forming many new convective cells at low levels in the later stage of seeded clouds. Using the same model, but for a case in Beijing, Xiao et al. (2006) showed that the seeding effect in the region of maximum supercooled water (temperature range 0 to $-10°C$) by AgI is better than that by liquid CO_2. In the region of maximum updraft (temperature range $+8°C$ to $-7°C$), liquid CO_2 is better than AgI for rain enhancement, and vice versa for hail suppression.

5.2 *Field experiments*

Zhou et al. (2004) studied the difference in microphysical characteristics between the seeded and unseeded stratiform clouds by analyzing the PMS data obtained during an artificial precipitation event in Liaoning Province of Northeast China. They found that the effect of seeding AgI on the microphysical structure of stratiform cloud is obvious. After seeding, the concentration of the ice (or snow) crystals increased from 618 m^{-3} to 2267 m^{-3}, water content increased from 0.10 g m^{-3} to 0.17 g m^{-3}, the concentration of the cloud droplet decreased from 34.38 cm^{-3} to 8.97 cm^{-3}, and supercooled liquid water content decreased from 0.015 g m^{-3} to 0.005 g m^{-3}.

Liu et al. (2005b) analyzed the observational data obtained with PMS during a rain enhancement operation in precipitating stratus in Jilin Province of Northeast China. They showed that different cloud types have different supercooled water content and cloud droplet number concentration. The estimated rainfall enhancement potential of the three types of clouds they observed were up to 41.3% for nimbostratus (Ns), about 28.4% for stratocumulus opacus (Sc op), and 26.6% for altostratus translucidus (As tra).

Based on the PMS data obtained during a returning weather process, Yang et al. (2005) found that the stronger precipitating cloud bands have abundant liquid water content and ice crystals, indicating better natural seeding potential. The cold cloud seeding was tested with the PMS by aircraft measurement in Shandong Province of East-central China in spring of 2000 by Wang and Lei (2003). They reported that liquid water content was decreased, the ice crystal concentration increased, and the particle size distribution widened in the diffuse zone in the five minutes after seeding.

6. Cloud physics and lightning

Lightning is produced by severe thunderstorms and related tightly to other weather disasters such as heavy rain, downburst, hail, and tornado. In addition, lightning activity may be a sensitive indicator of global or local climatic variation. The lightning characteristics and their relationship with the microphysical, dynamic features, and electrical structure of thunderclouds in different geographic and climatic zones have been one of the important issues receiving great attention in China.

6.1 *The spatial and temporal variations of lightning characteristics in China*

With grounded lightning detecting and locating technology as well as the OTD (Optical Transient Detector)/LIS (Lightning Imaging Sensor) database, the characteristics and parameters of the lightning discharges in different areas were obtained (Qie et al., 2003; Ma et al., 2005a,b). Their analysis showed that (1) the Lightning Density (LD) of China's continent regularly varies with latitude and distance off coast, with 2.5 times greater occurrence over the eastern than the western area of China, which is consistent with the varying trend of annual mean precipitation. (2) The regional differences in LD distribution are closely related to mesoscale orographic forcing. On the coastal land, the high LD centers appear in regions where mountains, hills and large cities are located. This seems to be related to the interaction between the sea-land breeze and mountain-valley wind or city heat island effect. (3) Lightning activity on the Tibetan Plateau is found to be a continental-type behavior, which exhibits diurnal variation with a single peak at 1600 LST and annual variation with a single peak in June.

6.2 *Lightning discharges and electric charge structure of thunderclouds*

The three-dimensional spatial and temporal development of impulsive VHF (very high frequency) radiation events during lightning discharges in two supercell thunderstorms was analyzed based on the data measured by the lightning mapping array (LMA) system with high space and time resolution (Zhang et al., 2006a,b). The results indicated that the charge structures in the main part (convective region) of the thunderstorms are inverted tripole while a number of positive cloud-to-ground (CG) lightning discharges occured in the two thunderstorms. The positive CG lightning discharges occurred in main part of the thunderstorms and originated from the positive charge region located at the middle part of the thunderstorms. The negative charge region located at the upper part of anvil produces a lot of negative CG lightning discharges. The charge region in the lower part of the thunderstorm plays an important role for the occurrence of CG lightning from the charge region above it.

The analysis of Zhang et al. (2002) revealed that intracloud (IC) discharges occur not only between the upper positive and middle main negative charge region, but also within the inverted polarity between the lower positive and middle main negative charge regions. Their results further confirmed the existence of the lower positive charge region involved in the lightning discharge. They also found that the inverted charge structure opposite to the normal polarity appears in some storms or at a certain stage of the storm development.

Qie et al. (2005) studied the characteristics of lightning discharge and charge structure in the northeastern part of the Tibetan Plateau on the basis of surface electric field measurements in 6 sites and high-speed digital camera records. It was estimated that a sequence of 30 flashes are produced from a storm with a tripole structure in the mature stage. Most of the IC flashes occur in the lower part and only a few occur in the upper part of the thunderstorm.

Tan et al. (2006a,b) reproduced the fine channel structure of IC and CG lightning flashes in different electric structures of thunderstorms using an improved Stochastic Lightning Model coupled into the 2-D and 3-D cumulus models of CAMS. Their results indicated that both types of positive and negative polarity IC flashes appear and that their channels exhibit the bi-level branched structure whenever the positive (or negative) potential well is collocated with an upper negative (or positive) well and its size extending along the horizontal is greater than that along the vertical.

6.3 *Relationship of lightning activity with climatic changes*

Based on the data from the two satellite detectors, OTD (five years) and LIS (eight years), and the NCEP (National Centers for Environmental Prediction) reanalysis data, Ma et al. (2005c) did a reanalysis of the response of the global and regional lightning activity to temperature variations. The results showed that on the interannual time scale the global total flash rate has a positive response to the variation in global surface air temperature, with the sensitivity of 17%±7% K^{-1}. In addition, Ma et al. (2005b) found the LD positive anomalies in Southeast China and adjacent coastal areas associated with the 1997/98 El Niño event.

7. Clouds and climate change

7.1 *Cloud climatology*

The International Satellite Cloud Climatology Project (ISCCP) D2 dataset has been used in a few studies to analyze the global and regional cloud amount variation over the past 20 years. Ding et al. (2004, 2005) showed that the global cloud amount distribution is mainly affected by atmospheric circulation and has remarkable regional features. Liu et al. (2003g) studied the climatic characteristics of clouds over China observed by the ISCCP compared to routine surface observation. According to their analysis, there were a decrease of 5% yr^{-1} in the total cloud amount over the North China Plain during the period 1984–1994 and a decrease of 10% yr^{-1} in the low-cloud amount over the Sichuan Basin of Northwest China during the period 1975–1994. The most manifest decrease (40% yr^{-1}) in the low-cloud amount was found over Chengdu, near the center of the Sichuan Basin, for the period 1975–1985. Liu et al. (2004) studied the spatial distribution and temporal variation of cloud amount over China with the ISCCP data. It was concluded that the cloud amount increased in Northeast China, and decreased in west and North China during the period 1983–2001. ISCCP data were also used for the comparison and evaluation of a regional numerical model by Li and Yu (2006).

7.2 *Clouds and radiation*

Almost no cloud field on Earth is horizontally and vertically uniform, but most studies on cloud radiation are based on the assumption of plane-parallel radiative transfer. Hu and Liu (2004) gave an overview of the theory of 3-D multimode radiative transfer and developed a code based on this theory and the radiative transfer model, DISORT, to investigate the influence of the sides of the finite clouds on cloud shortwave absorption. Zhang et al. (2005) computed the cloud shortwave radiative forcing in Southeast China using the cloud radiative parameters retrieved from the GMS (Geostationary Meteorological Satellite) data.

The impacts of cloud radiative transfer processes on precipitation were studied using a two-dimensional cumulus model (Zhao et al., 2003). Numerical results showed that cloud top cooling radiation and heating at the cloud base due to longwave radiation could enhance convective processes within clouds by modifying the vertical temperature structure in the cloud. Further, Zhou et al. (2006) proposed a method to quantitatively estimate the effects of radiative transfer process on precipitation by defining equivalent radiative cooling/heating which is combined by radiative cooling/heating and the vertical velocity variation ascribed to radiative transfer processes. This algorithm was verified by modeling a long period rainfall case in June 2002. The results showed that the radiative transfer process enhances diurnal precipitation variation by increasing the nocturnal rainfall and suppressing the daytime's as well as the total rainfall. The effects of radiation on a mesoscale precipitating system was investigated during a severe storm in South China on 8 June 1998 (Zhou et al., 2005c). The results suggested that the rainfall patterns do not differ too much for the various radiation schemes used in the numerical calculations, but rather influence the rainfall intensity in the central areas. As mentioned in section 3.3, the impact of cloud droplet spectrum on the microphysics and radiative processes was studied by Zhou et al. (2005b,c).

7.3 *Atmospheric aerosols and clouds*

Huang et al. (2005) analyzed the PMS data on stratus cloud microphysical properties in Hebei Province of East-central China during October 1990 and April 1991. They found that there is a positive correlation between aerosol number concentrations below the cloud base and cloud droplet number concentrations. Using a mutil-component size-resolving aerosol model, Zhao et al. (2005a,c) investigated the role of sea-salt in marine cloud microphysical processes. They showed that sea-salt particles are activated into cloud drops in the initial cloud development, and sea-salt activation decreases supersaturation by consuming water vapor and suppresses nss-sulfate activation. Nss-sulfate indirect forcing may be overestimated in some conditions (such as when the updraft is low) because of the presence of sea-salt particles.

Ice nuclei (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. Observations in Beijing showed that the concentrations of IN, which could be activated at $-20°C$, increased about 15 times from 1963 to 1995 (You et al., 2002b). Using the CAMS 3-D convective cloud model, Li et al. (2004a) studied precipitation processes over the Beijing area for the period between June and September 1996. They conducted numerical experiments by supposing that the concentration of IN had increased 5 times. The model results indicated that for most precipitation processes, the height of cloud tops, the area of cloud tops, and the quantity of ice crystals increase, and the size of ice crystals decreases, leading to the change in the radiant properties of clouds. 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). They found that the cold cloud reflectivity had changed over some areas for this period. For the case of the Beijing area, cold cloud reflectivity changed nonlinearly, with an increase over the first 10 years and a decrease over the last 10 years. They inferred that the ice nuclei may have an effect on cold cloud reflectivity.

Zhao et al. (2006b) studied the relationship between cloud spectral relative dispersion (ε) and cloud droplet number concentration ($N_{\rm c}$) using a large amount of aircraft measurements of cloud droplet size distributions. The results indicated that the value of ε varies between 0.2 and 0.8 when N_c is low (about 50 cm^{-3}), and converges towards a narrow range of 0.4 to 0.5 when Nc is higher. Because the distribution of the cloud droplet size is an important parameter in estimating the first indirect radiative effect of aerosols on the climate system, the uncertainty in the corresponding radiative forcing can be reduced by 10–40% (depending on N_c) under high aerosol loading. This finding is important for improving climate change projections, especially for the regions where aerosol loading is high and continues to increase.

Huang et al. (2006b) studied the effects of dust storms on cloud properties and Radiative Forcing (RF) over Northwest China using the data collected by MODIS and the Earth's Radiant Energy System (CERES) scanning radiometer on the Aqua and Terra satellites. They demonstrated that on average, 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. Due to changes in cloud microphysics, the instantaneous net RF is increased from -161.6 W m^{-2} for dust-free clouds to -118.6 W m^{-2} for dust-contaminated clouds. By analyzing the satellite data from ISCCP, MODIS and CERES, Huang et al. (2006a) showed that the water path of dust-contaminated clouds is considerably smaller than that of dust-free clouds, and there is a significant negative correlation between dust storm index and ISCCP cloud water path. They inferred that 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.

8. Conclusion and remarks

In our review of China cloud physics research from 2003 to 2006, we see increasing intestest in studying cloud physics from a wide variety of topics covering cloud field experiments and planned weather modification, relationships between cloud physics and precipitation, hail, lightning, and aerosols-cloud-radiation interactions. This is driven by an interest in solving the complex problems of climate change, weather forecasting, the growing demand for fresh water, and agriculture purposes. We believe that cloud physics and planned weather modification is still an important direction and an active research field both theoretically and in measurements in future years.

Aircraft measurements have provided important physical evidence about in-cloud conditions in China. New onboard instrumentations for aerosol and cloud observations have widely been used in the most parts of North China during the period 2003–2006. But we should realize that there are still large uncertainties existing in quantifying the spatial and temoral character of cloud and precipitation. Much work will be needed for a comprehensive evaluation of the quality of these data. A systematic analysis of the data with comparisons of model simulations should also be performed for the understanding of the microphysical mechanisms behind the variations in cloud properties.

Planned weather modification in China attracts more attention from the public and the local governments in many provinces due to fresh water and agriculture requirements. Although the development of a scientifically accepted cloud seeding technology is probably several years away due to a relatively poor understanding of purely statistical evaluations for seeding effects, planned weather modification in China offers the unique opportunity to actively experiment with clouds. We believe that more physical oriented measurements would not only improve our knowledge about natural cloud and precipitation processes, but also help us to better understand how anthropogenic activities affect cloud microphysical properties. This requires us to do more work on interpreting aircraft observations of rapidly evoling, small-scale convective events into appropriate spatial and temporal quantities useful for model evaluation.

The comprehensive field experiments have shown that the precipitation microphysical process of stratiform clouds in North China observes basically the "seeder-feeder" mechanism. The frontal precipitation cloud system is an important seeding object for artificial precipitation and generally has the typical structure of "seeder-feeder" cloud. While most studies have indicated the importance of cold cloud process in rainfall, some have argued that the warm rain mechanism plays an important part in the precipitation development of cloud.

In addition to the microphysical conditions, the importance of the lifting movement, which induces cloud formation, and the water vapor content in the lifting air mass for the choice of the cloud seeding location and time in weather modification has been emphasized. Concurrent measurements of cloud microphysical parameters, as well as the vertical speed and water vapor in the lifting air mass need to be strengthened in future intensive field experiments. More conditions than cloud structure should be considered for the assessment of seeding potential in artificial precipitation.

The mechanism of cave channels (CC) has been proposed, and would provide one of the scientific bases for hail suppression. Although there are a few reports on the verification of the CC mechanism by model simulations and Doppler radar observations, more work is needed to confirm the CC phenomenon and reveal the mechanisms associated with the accumulation of particles.

There have been increasing studies and usage of satellite data focusing on both macro- and microphysical characteristics of clouds in China during the last four years. Many cloud parameters imaged from satellites, such as liquid and ice water content, cloud top temperature, cloud cover, cloud optical thickness, cloud drop effective radius, and 3-D structure of rainfall rates have been used for various research from cloud microphysics, to mesoscale precipitation, to climate change. The effect of the precipitation enhancement operation with the aircraft has been viewed by the satellite, which highlights the potential application of satellite images in the operation of weather modification. Much more work is needed for the retrieval of cloud microphysical parameters with Chinese satellite data.

Due to the limitation of aircraft measurements in deep convective clouds, other measuring methods such as microwave radiometer remote sensing and video images are also useful, in particular for the study of cloud microphysical processes in heavy rainfall. This may be important and challenging work in the field experiment of thunderstorms over China. It has been found that ice-phase microphysical processes of clouds may have significant effects on precipitation formation and heavy rainfall. Measurements of ice-phase particles should be strengthened in future field experiments.

Various cloud models, which were originally developed in 1980s and 1990s by different Chinese groups/institutes, have been used in studies over the last four years. These include 0-D, 1-D, 2-D or 3-D cloud model, stratiform or convective model, and size-resolved or bulk cloud model with various cloud microphysical processes included. Model results have generally been compared with cloud macro- structure retrieved from radar echoes and satellite data. Much work needs to be done on the comparison between model simulations and microphysical parameters obtained, e.g., with the PMS, in future studies. This will be most important for the understanding of microphysical processes occurring in clouds.

The interactions between aerosol, cloud and radiation processes are one of the leading research fields both in global climate changes and short-term weather forecasting. Measurements and theoretical studies in this field have been carried out in China during the past four years. A significant challenge is to study the role of atmospheric chemistry in cloud physics and precipitation. Correlations between aerosol pollution and cloud microphysical properties have been found through the analysis of historical data. While the research on weather modification has focused more on large particles, the research on aerosols, clouds, and radiation interaction should focus more on fine and ultra fine particles. Integrated space-, air-, and ground-borne observations of aerosol, cloud and radiation parameters are suggested to get invaluable information on the issues. Coupled models that include aerosol and cloud chemical/physical processes and radiative transfer need to be developed and applied in the studies related to climate changes. The urbanization effects including pollutant emissions and land surface change on cloud and precipitation processes pose a new challenge in both regional weather forecasting and climate change.

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