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Particle size spectra and possible mechanisms of high ice concentration in nimbostratus over Hebei Province, China

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ABSTRACT

By employing the three-aircraft measurements combined with Radar and satellite imageries, microphysical structures of a nimbostratus cloud caused by a westerly trough in Zhangjiakou City, Hebei Province on May 1, 2009 are analyzed in this paper, focusing on vertical distribution of PSD (particle size distribution) and the 2D imagery at a variety of altitudes and temperatures. PSD generally appeared to conform to an exponential size distribution, with well-correlated linear fits between the log of the number concentration and particle diameter. Similar to previous studies, analyses of PSD parameters N_0 and λ of empirical function $N_s = N_0 \exp(-D\lambda)$ show that particle growth falls into three stages according to spectral trajectory. The positive shift in both N_0 and λ at temperatures higher than −8 °C in our study was likely caused by extension of supercooled droplet spectra, and according to earlier studies, the effect of large droplets on ice concentration can also be proved by seeking correlations between ice particle concentration and the concentration of cloud droplets exceeding a certain diameter. However, 2D imageries showed that only a few (<10%) ice particles were pristine in the −3 to −10 °C temperature range. The large number of unidentifiable ice particles could have originated from shattering of larger drops during freezing in fall. In the region of −10 to −15 °C, the secondary ice production mechanism may be the dendrite crystal–crystal collision breakup. Moreover, other mechanisms including deposition growth of small ice particles within the convective turrets near cloud top and activation of anthropogenic pollutant such as mineral dust, biological, and oxidized organic aerosol particles may also affect ice particle concentrations.

1. Introduction

In the 1930s, Bergeron (1935) proposed that when ice crystals and supercooled droplets coexist in a cloud, different super saturation rates near the surface of ice and liquid phase hydrometeor will lead to the preferential growth of ice particles by consuming supercooled droplets and further to the formation of precipitation particles. Since then, interest in ice particles in clouds has centered on three topics: their origins, their concentrations and their growth (Hobbs and Rangno, 1985). Precipitation formation mechanisms in different locations may differ dramatically from each other. When the cloud top reaches temperature lower than 0 °C, ice develops and precipitation can develop through different microphysical processes; and the number concentration and size spectra of particles, both of which are key factors in cloud seeding, also vary dramatically with different synoptic backgrounds (Bruintjes, 1999). Based on Braham (1986), the factors that hinder the research mainly lie in two aspects: the large scale variability and an incomplete understanding of the physical processes involved. The investigation thus should concentrate on microphysical processes of precipitation formation.

For decades, airborne probes have been applied to facilitate the measurement of precipitation processes throughout mixed phase clouds and results show the occurrence of high ice concentrations there. Ice splinter produced during riming could account for the relatively high concentration of ice particles in clouds that encompasses temperature within −2.5 to −8 °C.

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Crosier et al. (2011) and Crawford et al. (2012) present observations which support rime-splintering mechanism in cumulus and layer stratiform clouds respectively. However, ice splinters are generally assumed to grow into pristine ice crystal habit. And Rangno and Hobbs (2001) provide evidence for various ice multiplication mechanisms (e.g. riming splintering, shattering of frozen drops) in the arctic stratiform cloud with detailed measurements showing that over 68% of ice particles were not pristine. Recently, Sun et al. (2012) investigated the impact of rime splintering in shallow warm cumulus, and Yano and Phillips (2011) performed numerical studies on the effects of ice–ice collision in mixed phase clouds. In many studies (Herzegh and Hobbs, 1985; Lo and Passarelli, 1982; Field, 1999; Heymsfield et al., 2002) size spectra of ice particles are confirmed to change to adjust to such microphysical processes as deposition growth, aggregation and ice multiplication at various altitudes and temperatures within the precipitation system. Besides, these studies see correlations between particle size spectra and temperatures. In addition to information of particle size distribution, the 2D imagery probes (Hou et al., 2010; García-Ortega et al., 2008) also provide a further insight into particle shapes and habits. However, ice particles shattering on the inlet and tips of airborne probes produce small ice artifacts that can be a possible source of error included in measurements of ice particle size distributions (Jensen et al., 2009; Lawson, 2011).

This paper involves an investigation of PSD collected by probes installed in three aircrafts manufactured by PMS and DMT Inc., in a westerly trough precipitation system in Zhangjiakou City, Hebei Province, China on May 1, 2009, during the field study of R&D of Key Technology and Equipment for Weather Modification.

Subsequent sections cover the following aspects of nimbostratus: the vertical and horizontal distributions of size spectra of both liquid and ice/snow particles; the relationship between temperatures and ice crystal habits; the influences of different ice enhancement processes; and the relationship between the concentration of ice particles and supercooled liquid particles. A comparative study between our findings and those prior investigations of spectral changes and particle imageries is also included.

2. Synoptic situation

The observation data used in this section mainly involve surface rainfall and Radar reflectivity. The surface rainfall was collected during the field study, and the observed Radar reflectivity originally provided by LACS (Laboratory of Cloud-Precipitation Physics and Severe Storms, Institute of Atmospheric Physics) was derived from base reflectivity scans of the vehicle-carried X-band Doppler weather Radar located in the suburbs of Zhangbei City, Hebei Province. The resulting products were binned into 5-dB*Z* intervals and the synoptic map was based on the NCAR reanalysis dataset with a 1×1 grid resolution.

The synoptic situation on 1 May, 2009 over Zhangjiakou City was primarily influenced by a shallow upper level trough. This northeast–southwest oriented trough appeared in west Baikal Lake, mid-Inner Mongolia and Hetao area on 500 hPa map for 0200 LST (all times Local Standard Time, LST, 8 h later than UTC). In the 850 hPa synoptic analysis for 0200 LST in Fig. 1B, water vapor was transported by the south warm wet airflow from the Indo-China Peninsula to the westerly trough system. Influenced by a strong west wind back of the trough and northward subhigh displacement, the trough advanced through north Inner Mongolia and North China. At 0800 LST the 850 hPa chart depicts a closed cyclonic feature lying to North China (N45°, E128°), and Fig. 1D unveils the orientation of the trough at 0800 LST.

As the 850 hPa westerly trough moved eastward (Fig. 1D), the satellite imagery in Fig. 2 showed a broad cloud shield associated with the system, extending from Central China to the Pacific coast. Most parts of Eastern China at 0000 LST were covered by a cloud band along Inner Mongolia — Central China and the relative humidity exceeded 90% on 850 hPa chart. At 0800 LST, the cloud band moved to Northeast China.

Fig. 3 reveals the observed plan position indicator (PPI) of Radar intensity from the X-band vehicle-carried Doppler weather Radar located in the suburbs of Zhangbei City on 1 May, 2009, 0838 to 0959 LST. The rainband was approximately parallel and oriented to axis SSW to NNE and moving at the speed of 7.78 $\mathrm{m\ s^{-1}}$ perpendicular to the rainband. And the considerable substructures contained in the rainband are cores with Radar reflectivity exceeding 30 dBZ. This rainband, forced by a cold front, contributes significantly in producing precipitation over the study field from approximately 0800 LST 30 April to 1130 LST 1 May. The three aircrafts flew in the mixed phase clouds on 1 May, 2009 in the southeast of the Radar site, and the majority of the aircraft sample time was spent flying along northeast to southwest. The Radar at a suburb of Zhangbei City performed Range Height Indicator (RHI) Scans along 150 radial (perpendicular to the flight tracks) and Plan Position Indicator (PPI) Scans. During the flight detection, the RHI shows the cloud top height and the corresponding temperatures are 5500 to 6000 m and −16 to −19 °C respectively, roughly in consistence with those detected by aircraft. See Fig. 3 for an overview of the flight location, as well as the location of the Radar site.

From 30 April, 2009 to 1 May, 2009 precipitation rates were measured with rain gauges at 232 stations in Zhangjiakou City. The accumulated precipitation from 176 stations exceeded 5 mm and 78 stations 10 mm. The average precipitation was 8 mm. The maximum of 13.6 mm appeared in Chongli County.

3. Field study and instrumentation

R&D of Key Technology and Equipment for Weather Modification mainly aimed to study microphysical processes of stratiform cloud in North China and build datasets for improvement of weather modification technologies. In Fig. 4, the field study (area: N 40°35′, E 113°35′; N 40°35′, E 115°30′; N 41°40′, E 115°30′; N 41°40′, E 113°50′) made use of ground-based instrumentation (including Radar measurements and precipitation measurements) to measure and investigate the precipitation system passing the field study area. The aircrafts and instruments from three different organizations are listed in Table 1. To study the precipitation growth at various levels within the stratiform cloud, the flight pattern within the precipitation event was designed to consist of vertical stacks of horizontal flight legs ranging from 50 to 120 km horizontally, 1 to 6 km in altitude, and 17 to −19 °C in temperature. Detailed flight tracks of the three aircrafts are illustrated in Fig. 4.