Atmospheric Environment 45 (2011) 665–672

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Impact of aerosol particles on cloud formation: Aircraft measurements in China

Qiang Zhang [a], Jiannong Quan [a,b,*], Xuexi Tie [c], Mengyu Huang [a], Xincheng Ma [a]

[a] Beijing Weather Modification Office, Beijing, China
[b] Institute of Urban Meteorology, CMA, Beijing, China
[c] National Center for Atmospheric Research, Boulder, CO, USA

A R T I C L E I N F O

Article history:
Received 17 June 2010
Received in revised form
12 October 2010
Accepted 15 October 2010

Keywords:
Heavy aerosol pollution
Aircraft measurements
Cloud formation
CCN and LWC
Beijing

A B S T R A C T

In-situ aircraft measurements of aerosols and clouds of 7 flights during the period from July to September of 2008 are analyzed in Beijing, China. The measured aerosol concentrations indicated that the Beijing region was highly polluted by aerosol particles. The impact of heavy aerosol particle loadings on cloud formation is studied. The microphysical characters of clouds (including number concentrations of cloud droplets (Nc), cloud droplet radius (Rc), liquid water content (LWC)), and number concentrations of aerosol particles (Na) were measured during the experiments. The aircraft measurements indicated that under high aerosol particle conditions, large number of cloud droplets was formed with small size of droplets. By contrast, under low aerosol particle conditions, the formation of cloud droplets was limited by the number of Na. In this case, small number of cloud droplets was formed with large size of droplets. The number concentrations of cloud droplets were sensitivity to LWC under high aerosol particle conditions. With low LWC value ($<0.1\ g\ m^{-3}$), the Nc was slowly increased with the Na. For example, the cloud droplets were increased from 200 to 300 cm^{-3}, while aerosol particles were increased from 1000 to 6000 cm^{-3}, indicating that a large amount of aerosol particles were unchanged under low LWC condition. By contrast, with high LWC value ($>0.5\ g\ m^{-3}$), the activation of aerosol particles to become cloud droplets was significantly enhanced. For example, the cloud droplets were increased from 700 to 1900 cm^{-3}, while aerosol particles were increased from 1000 to 6000 cm^{-3}, suggesting that a large amount of aerosol particles were converted to cloud droplets when there were enough LWC for supporting such conversions. This study also suggests that the Rc was also very sensitivity to the LWC values. The increase in the LWC values led to significant increase in the size of cloud droplets.

1. Introduction

Atmospheric aerosols have important effects on cloud formation, precipitation, and climate changes (IPCC, 2007; Ramanathan et al., 2005). For example, aerosol particles change the formation and properties of clouds (Andreae et al., 2004), radiative energy budget of the Earth (Andreae et al., 2005), atmospheric stability (Zhao et al., 2006), and deep convective clouds (Rosenfeld et al., 2008). At the present, we do not fully understand the above mentioned process, especially how aerosols affect cloud formation, water cycle, and radiant energy budget in the climate system (Stevens, 2008).

China is one of the regions with heavy aerosol loadings (Li et al., 2007; Tie et al., 2006), and the high concentrations of aerosols are mainly resulted from human activities, and dust storms (Zhang et al., 2006; Shao et al., 2006; Chan and Yao, 2008). Studies regarding the aerosol, cloud, and precipitation in this region indicated that the high concentrations of aerosols have already affected the clouds, precipitation, and climate. For example, Jin and Shepherd (2008) analyzed the interactions between aerosols and clouds/rainfall in warm season in eastern China based on the analysis of satellite data. Their study suggested that aerosols have more effects on cloud formation than convective rainfall, and the effects on cloud formation were more frequents over ocean than over land. Zhao et al. (2006) studied a long-record of precipitation, satellite aerosol data and meteorological sounding data over central-eastern China. Their study suggested that aerosols (especially black carbons) enhanced atmospheric stability, and the enhancement in atmospheric stability tend to depress upward motion and precipitation in central-eastern China. Menon et al. (2002) studied the climate effects of black carbons on climate in China and India. Their study suggested that black carbons affect large scale circulations and hydrologic cycles with significant regional climate effects.

* Corresponding author at: Beijing Weather Modification Office, Beijing 100089, China.
E-mail address: quanjn1975@gmail.com (J. Quan).

1352-2310/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.atmosenv.2010.10.025

In the previous studies, cloud data is mainly collected from satellite observations, and detailed microphysical parameters of clouds in central-eastern China are poorly understood. Thus, in-situ measurements of aerosols and clouds are urgently needed in order to study the impacts of aerosol particles on cloud formation, precipitation, and climate change in this region.

There were several studies regarding the aircraft measurements of aerosols and cloud droplets in central-eastern China. For example, Deng et al. (2009) showed that under very low cloud liquid water content, the measured cloud droplets number concentrations (with high aerosol concentrations) were less than 100 cm^{-3}, indicating LWC plays important roles in controlling the number concentrations of cloud droplets. In this study, the detailed aerosol particles and cloud droplets were measured under different LWC conditions during the period from July to September, 2008. This study intends to address the following issues; (a) to analyze the measured characteristics of aerosols, cloud condensation nucleation (CCN), and cloud droplets in central-eastern China; (b) to analyze the relationship between aerosols and cloud droplets; and (c) to study the impact of heavy aerosol concentrations on cloud formation. The paper is organized as the follows. In Section 2, we describe the experimental method; including the instruments and measurement data. In Section 3, the measured result is analyzed and discussed. The summary of the results is given in section 4.

2. Data and method

2.1. Instruments on the aircraft

Several instruments are mounted on an aircraft (Y12) for measuring the concentrations of aerosol particles in different size bins, CCN number concentrations, and the size distributions and number concentrations of cloud droplets over the Beijing region, China. Aerosol particles ranging from 0.10 to 3.0 μm in diameter are measured by a Passive Cavity Aerosol Spectrometer Probe (PCASP-200). During the measurement, three heaters in PCASP were turned on, which can reduce the RH to 40% in the inlet air (Strapp et al., 1992). Cloud droplets with diameter ranging from 0.6 to 50 μm were measured by a Cloud, Aerosol and Precipitation Spectrometer (CAPS). In this study, only particles with diameter of larger than 2 μm were counted as cloud droplets. The LWC in cloud was calculated based on the measurement of volume concentration of cloud droplets. In addition to cloud droplet measurement, the activation of aerosol particles to CCN was also measured by a CCN counter (CCNC; Droplet Measurement Technologies Inc., DMT) during the flights. This instrument operates in a continuous flow mode, making measurements of CCN in every second. The CCNC operates at a single supersaturation, from the range 0.07–2.0%, with an air flow rate of 500 $cm^3\ min^{-1}$. During flights, the super-saturation point was set as 0.3%. The supersatuation given by DMT CCNC during field measurements might exist some deviation. According to the work of Rose et al. (2008), the relative deviations of supersatuation can reach up to 10%, especially at low supersaturation, which will influence the CCN concentration correspondingly. The Meteorological measurements included location, temperature, relative humidity, barometric pressure and wind using with AIMMS-20 (Aircraft Integrated Meteorological Measurement System, Advantech Research Inc.). PCASP and CAPS were mounted on the wings of aircraft, which allowed air to directly follow into the instruments. For cloud droplets, they were detected with environmental pressure and temperature. For aerosol particles, they were detected with environmental pressure, and the heaters in PCASP were turn on during the measurement. For CCN measurement, the inlet (Male Run Tee 15MF-6 by Truly Tubular Fitting Corp) was mounted on the top of aircraft, and connected to a stainless steel tube. In this experiment, we didn't perform a RH control on CCNC.

ALL the instruments (PCASP, CAPS and CCNC) are calibrated by DMT every year before aircraft measurements are taken placed. In addition, the PCASP and CAPS are calibrated using polystyrene latex spheres (PSL) by Duke Scientific Corporation every month. The size distribution, total volume of particles, mean diameter, and number concentrations of aerosol particles are online analyzed during measurements. The measured cloud droplet number concentration was sampled and corrected for dead-time and coincidence according to the method suggested by Brenguier and Amodei (1989) and Baumgardner et al. (2002). The sampling interval was 1 s during all flights. The aircraft flight altitudes were from surface to 6 km. During the cloud detection, the aircraft horizontally penetrated into small cumuli and other non-precipitation clouds, but was not able to enter strong cumuli clouds. The horizontal scale of small cumuli clouds were often about several hundred meters, and a few cumuli clouds were about 1–2 km s. The field measurement was carried out in the Beijing region, China during the period from July to September 2008. The detailed flight information is shown in Table 1.

2.2. Data processing

According to previous studies, there were several criterions to define the appearance of clouds, such as (a) Nc > 10 cm^{-3} (Rangno and Hobbs, 2005; Stith et al., 2006); (b) LWC > 0.01 g m^{-3} (Gultepe

Table 1
Flight Information regarding the 13 cloud detections.

Date	Cloud height (meter)	Sampling number	Aero under cloud (cm^{-3})	Cloud droplet concentration (Nc, cm^{-3}) and size(Rc,μm) under different LWC(g m^{-3})							
				<0.1		0.1–0.3		0.3–0.5		>0.5	
				Nc	Rc	Nc	Rc	Nc	Rc	Nc	Rc
29/Jul.	2071–2439	592	6021.97	164.56	2.01	1512.88	3.61	1934.39	4.26	2212.78	5.04
30/Jul.	2442–2592	413	2672.73	374.46	2.27	1276.08	3.41				
31/Jul.	679–957	65	4664.36	309.24	2.68	1572.68	3.77	1346.50	5.30	2218.78	5.57
31/Jul.	2474–2552	210	244.71	187.76	4.97	184.17	7.86	264.78	8.73	284.55	10.10
31/Jul.	2120–2242	68	374.58	56.04	7.56	187.85	8.58	273.82	9.34	475.69	9.57
13/Aug.	1626–2088	98	3375.45	92.86	4.33	304.97	7.02	600.09	6.96	1482.83	7.34
13/Aug.	639–769	277	7337.97	352.11	2.52	1833.65	3.71	2536.2	4.02		
21/Aug.	2305–2697	107	1249.14	401.86	5.18	875.97	6.48	764.32	8.56		
21/Aug.	1145–1433	1791	4284.22	391.47	5.69	928.64	6.34	912.19	7.83	1170.03	8.21
21/Aug.	3333–3668	1312	829.15	56.56	8.09	464.75	6.61	500.43	7.55	653.9	7.36
9/Sep.	1400–1772	194	4786.51	242.05	6.57	766.49	6.60	1075.04	6.99	1372.99	7.52
9/Sep.	4256–4654	442	184.03	76.42	8.92	160.17	8.74	187.59	9.49	197.70	11.35
17/Sep.	665–889	73	6691.29	253.84	2.71	1690.13	3.87				