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Statistical analysis of microphysical properties and the parameterization of effective radius of warm clouds in Beijing area

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ABSTRACT

In this paper warm cloud microphysical parameters including cloud droplet number concentration (N_c), liquid water content (q_l) and effective radius (r_e) from 75 flights around the Beijing area during 2005 and 2006 are summarized. Average N_c (cm^{-3}) for Cu, Sc, Ac, As and Ns are 376 ± 290, 257 ± 226, 147 ± 112, 60 ± 35 and 60 ± 84, respectively. Many records of high N_c above 1000 cm^{-3} are observed. The large standard deviations indicate a large variation of N_c and q_l in this region. The maxima of q_l reach 1.4 g m^{-3} in Cu and 1.0 g m^{-3} in Sc, respectively. Different parameterizations of effective radius are examined with the in-situ data in this area. There are different ways to obtain the prefactor representing the relationship between effective radius and mean volume radius. Significant systematic errors are found to be at the large sizes when the prefactor is expressed with relative dispersion under the Gamma Distribution. Fixed prefactor of 1, which was widely used, even produces much larger error. A prefactor of 1.22 is found to be better than the former two methods by fitting with the observed data. The effective radius is further parameterized as functions of mean volume radius, liquid water content and cloud droplet number concentration. We suggest that the effective radius can be parameterized as $r_{e,p} \approx 1.20 r_v + 0.22\text{–}1.28/r_v^2$, which is a practical and more accurate scheme without too much computation complexity.

1. Introduction

Clouds, which cover about 60% of the earth's surface, can significantly influence the radiation budget by reflection and absorption of the solar and terrestrial radiation. High cloud condensation nuclei (CCN) concentration due to large amount of aerosol will result in a high cloud droplet number concentration and a small cloud drop size under constant cloud liquid water content (q_l) (Twomey, 1974). For example, the cloud droplet number concentration (N_c) can reach 1400 cm^{-3} because of the biomass smoke in Brazil (Reid et al., 1999). According to Zhao et al. (2006a), the reduction of precipitation in Eastern Central China (ECC) is strongly correlated to the high concentration of anthropogenic aerosol. In order to understand such interactions, we should learn more about the microphysical properties of clouds, such as cloud droplet number concentration, liquid water content, cloud droplet spectrum, cloud droplet mean radius (r_m), and cloud droplet effective radius (r_e).

At present, N_c is not able to be calculated in a realistic way in large-scale models and most of the meso-scale models because it varies over a large range and depends on several factors that are not easy to be predicted, such as the updraft velocity and the exact CCN available for activation. Many numerical weather prediction models and general circulation models adopt a fixed value (most commonly 100 cm^{-3} or 300 cm^{-3} for continents and 50 cm^{-3} for oceans) (Reisner et al., 1998). N_c was also a constant in previous climate models, for example, 600 cm^{-3} for continents and 150 cm^{-3} for oceans (Bower et al., 1994). Boucher and Lohmann (1995) related N_c to the sulfate aerosol

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Table 1
Previous measurements in ECC.

Date	Location	N*	Cloud type	N_c (cm^{-3})		q_l ($g\ m^{-3}$)		Rm or Re (μm)		Refer
				Avrg	Max	Avrg	Max	Avrg	Max	
1989.10.10	Shandong	1	Sc	<6	<6	/	0.005	<4	5	Chen et al., 1999
			As	/	370	/	0.145	/	~10	
1989, 1990, 1999	Shandong	5	Ac As Sc	10–20	~100	~0.03	0.18	/	/	Chen and Wang, 2001
1989, 1990, 1992	Shandong	27	Strf	58	140	0.057	0.36	~5	/	Zhang and Feng, 1997
1990–1993, 04–07	Hebei	60	Strf	62	833	0.04	0.49	4.5	/	Wu, 1994
1990.09–10										
1991.04.11	Hebei	1	Sc	50–100	<210	/	<0.04	~2	5	Sun et al., 1994**
1991.04.16	Hebei	1	Strf	/	<100	/	/	~4	~5.5	Liu et al., 1994
1991.05.24	Hebei	1	Sc	/	180	~0.02	0.05	~3	~4	Sun, 1994**
1991.05.25	Hebei	1	As	30	/	/	~0.17	~9	10	Wu et al., 1994
			Sc	<60	140	/	~0.09	~8	10	
1990.09–10	Hebei	12	Strf	79	838	0.03	2.7	3.5	11.5	Huang et al., 2005
1991.04								**5.5**	**15.8**	
1991.05.25	Hebei	2	Strf	/	<200	<0.06	<0.117	~10	<14	Yang et al., 2005
1992.06.21										
1999.05.17–18	Shandong	3	Strf	20–100	250	~0.005	0.035	~5	11.5	Su et al., 2000**
2000.04.14	Henan	2	/	44–49	578	~0.05	0.527	/	/	Jin et al., 2006

*N is number of flights, 'strf' means stratiform clouds, 'Avrg' is the average value, 'Max' is the maximum.
** Only the warm part is presented here. For most of the other work, super cooled water is also included.

mass concentration derived from a chemical transport model, and found that the regional distribution of radiative forcing and the land/sea contrast are very sensitive to the choice of N_c–sulfate relationship. Martin et al. (1994) concluded a relationship between N_c and the measured number concentration of aerosols just below the clouds for maritime aerosol in the range of 36–280 cm^{-3} and continental aerosols in the range of 375–1500 cm^{-3}. Ghan et al. (1997) predicted N_c prognostically in a GCM, assuming constant aerosol number concentrations. Lohmann et al. (1999) combined this prediction with the aerosol number from a calculated three-dimensional distribution, and the aerosol size and composition from a microphysical model.

Meanwhile, observations show that N_c occupies a wide range and varies greatly between different cloud types (Quante, 2004; Heymsfield, 1993) and in different parts of a cloud. Miles et al. (2000) collected the in-situ data reported in the existing literatures, including N_c, r_m, σ, q_l and r_e in marine and continental clouds observed all over the world. The average N_c in each continental cloud range from 15 to 680 cm^{-3}, with an overall average of 288 cm^{-3}, while q_l, r_m, σ and r_e are 0.19 (0.0005 ~ 1.0) $g\ m^{-3}$, 4.1 (0.5 ~ 8.9) μm, 1.55 (0.45 ~ 4.7) μm, and 5.4 (1.35 ~ 14) μm. In ECC, a lot of aircraft measurements have been made during the past two decades (Table 1). It's surprising that the average N_c are even less than 100 cm^{-3} (Chen et al., 1999; Chen and Wang, 2001; Huang et al., 2005; Jin et al., 2006; Liu et al., 1994; Su et al., 2000; Sun, 1994; Sun et al, 1994; Wu, 1994; Wu et al., 1994; Yang et al., 2005; Zhang and Feng, 1997). A question rising from these published measurements is why the N_c is so low in such a polluted region. An examination of N_c measurements in ECC is expected to improve the understanding of aerosol–cloud interactions in the intensive-human-activity region.

Size distribution of cloud droplets is another important parameter which has a significant impact on microphysical processes and the radiative properties of clouds. Cloud droplet spectral change can significantly alter the precipitation intensity (Zhou et al., 2005). But spectra can be predicted only in bin microphysics schemes, and are often set as a prescribed distribution in other models if needed (Dong et al., 1997). Actually, the effective radius, which is the ratio of the third to the second moment of the cloud spectrum, is a substitute to the spectra in radiation transfer models. The optical thickness, the single scattering albedo and the asymmetry factor are the three most important parameters needed to describe the radiative properties of clouds (Twomey and Bohren, 1980; Slingo and Schrecker, 1982; Martin et al., 1994). All of the three parameters can be expressed in terms of the effective radius (r_e) in liquid water clouds (Stephens, 1978; Twomey and Bohren, 1980; Slingo and Schrecker, 1982).

A big challenge for cloud microphysical modeling is the determination of r_e. Slingo's (1990) numerical study showed that a reduction of 2 μm in r_e (and a corresponding increase in N_c) or an increase of about 20% in liquid water path (LWP) would be able to offset the warming effect of doubling carbon dioxide. However, in most models, r_e is parameterized, instead of predicted. Effective radius was assumed to be constant (Slingo, 1989) or expressed as a function of liquid water content (Stephens, 1978; Fouquart et al., 1990) in early parameterization schemes. It's widely accepted that the effective radius correlates well with mean volume radius r_v (as Eq. (10)) (Pontikis and Hicks, 1992; Bower and Choularton 1992), which can be obtained from N_c and q_l. The effective radius then can be expressed as

$$r_e = \beta(3q_1/4\pi\rho_w N)^{1/3} = \beta r_v, \qquad (1)$$

where ρ_w is the water density. The prefactor β, a proportionality factor or scaling factor, was originally specified as a constant in layer clouds (Bower et al., 1994; Boucher and Lohmann, 1995). Theoretical derivation shows that the scaling factor is a function of relative dispersion,

$$\beta \approx \left(1 + 3\varepsilon^2\right)^{2/3} / \left(1 + \varepsilon^2\right), \qquad (2)$$