J12.4 SIGNIFICANT IMPACT OF AEROSOLS ON MULTI-YEAR RAIN FREQUENCY AND CLOUD THICKNESS

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1. INTRODUCTION

Many observational studies of aerosol indirect effects [*Rosenfeld and Lensky*, 1998; *Lebsock et al.,* 2008; *Koren et al.* ,2005, 2008; *Lin et al.* ,2006; *Bell et al.*, 2007] have shown aerosols either suppress or enhance precipitation. The explanation of the enhanced precipitation is that aerosols may suppress warm rain processes, cause clouds to reach higher level, and enhance ice rain processes [*Rosenfeld et al.*, 2008]. These observational results are also supported by a lot of cloud-resolving model studies [*Khain et al.*, 2004, 2005; *Fan et al.*, 2007; *Van den Heever and Cotton*, 2007; *Wang*, 2005]. In this paper, we conduct statistical analysis on the influence of aerosols on rainfall frequency and cloud properties using a variety of observations of aerosols, clouds, and precipitation at SGP from 1999 to 2008. The basic idea of our studies is to find evidences of the aerosol invigoration effect and factors controlling it.

2. DATA AND METHODOLOGY

The main data used in this study include the condensation nuclear (CN) number concentration, cloud liquid water path (LWP), cloud geometry, rain information, and meteorological conditions such as surface temperature, pressure, and wind speed observed at the ARM (Atmospheric Radiation Measurement) Southern Great Plains (SGP) site.

The rain rate data was divided into 3 bins based on LWP: 0-0.4mm, 0.4-0.8mm and larger than 0.8mm. For each bin, the data were further divided into several subsets based on CN number concentration from the most clean case (N:0-1000/cm^3) to the most polluted case (N:5000-6000/cm^3). Other methods to bin the data such as binning with equal sample sizes were also tested. In each subset, the rainfall frequency was calculated from the number of rain evens divided by the total number of observations. The CN number concentration one hour before rain evens was used to avoid the washout of aerosols by rainfall. The relationships between other variables and CN number concentration were also calculated using the same bins as CN number concentration.

3. CHANGES OF RAINFALL FREQUENCY FOR CLOUDS WITH DIFFERENT LWP

Figure 1 shows the rainfall frequency as a function of condensation nuclei number concentration for different LWP bins at SGP site during 1999-2008. Totally about 32,000 data points are included in the calculation for the whole period. The rainfall frequency for clouds with different LWP shows very distinctive behavior with the increase of CN number concentration. The rainfall frequency increases for clouds with high LWP but decreases for clouds with lower LWP with the increase of CN number concentration. For clouds with moderate LWP, the rainfall frequency shows no clear trend. The rainfall frequency as a function of CN number concentration in summertime only also

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shows the similar pattern as Figure 1. To avoid artificial effects, different ranges of LWP bins are used to test the results from both all seasons and summer only, which show very consistent patterns (not shown here). We also analyzed the dependence of many variables including the surface temperature, pressure, wind speed, and column water vapor on CN. Results show the surface temperature, pressure and column water vapor has no correlation with CN number concentration, indicating these factors are not likely to cause the complicated relations between rainfall frequency and CN number concentration. The wind speed shows negative correlation with CN number concentration presumably due to more pollutants accumulated under light wind conditions.

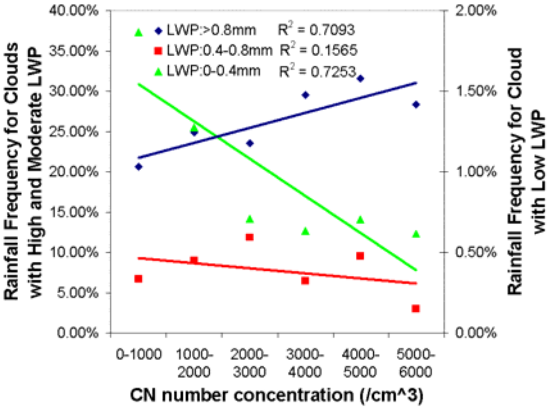

Figure 1. Rainfall frequency as functions of CN number concentration for different LWP bins at SGP site in all seasons during 1999-2008. For clouds with LWP larger than 0.0 mm but smaller than 0.4mm, the right Y axis is used to clearly show the change of rainfall frequency.

4. EVIDENCES OF AEROSOL INVIGORATION EFFECTS

The direct evidence of the aerosol invigoration effect is the increase of cloud top heights with aerosol loading as revealed by previous studies [*Koren et al.*, 2005, 2008]. To find such evidence, we first examined the frequency of occurrence of cloud top heights under different CN number concentration. The result is shown in Figure 2. When CN number concentration increases, the frequency of occurrence of lower cloud top heights decreases but the frequency of occurrence of higher cloud top heights increases. The averaged freezing level 3,300m which is obtained from eight-year sounding data at SGP site was marked as a vertical red line in Figure 2. The result indicates that more clouds reach above the freezing level when CN number concentration increases. This is the reason that the invigoration effect could happen.

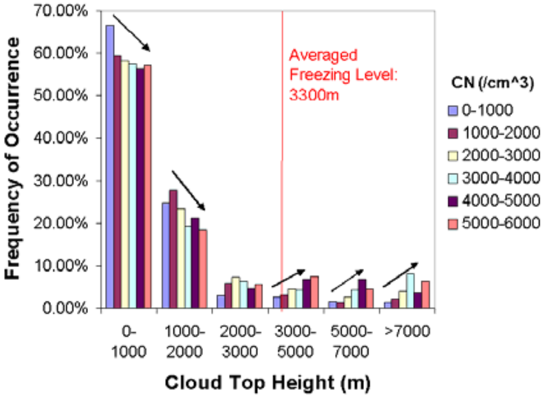

Figure 2. Frequency of occurrence of cloud top heights under different CN number concentration for clouds with bases lower than 1km.

The invigoration effect is also confirmed by the change of cloud thickness with CN number concentration as shown in Figure 3. Previous studies have shown that the invigoration effect is more obvious for warm base clouds [*Khain et al.*, 2005; *Bell et al.*, 2008]. Our results confirmed that. It is found that cloud thickness increases most significantly with CN concentration for low base clouds (cloud base <1km). But there is almost no increase of cloud thickness with ground-level CN for high-base clouds (3km<cloud base<4km), as one would expect. For moderate base clouds, the increasing rate falls in between.

The cloud base heights for all the three categories of clouds show almost no change with the increase of CN number concentration. Changes of cloud thickness with CN number concentration in summer only also show the same result.

The different strengths of the invigoration effect for clouds with different cloud base heights lead to different responses of the rainfall frequency to the increase of CN as shown in Figure 4. The data are divided into two categories: CBH<1km and 1km<CBH<4km instead of three to increase the sample sizes for high base clouds. There are totally about 14,000 in all seasons. The rainfall frequency increases dramatically for lower base clouds but slightly decreases for higher base clouds with the increase of CN number concentration. This implies that the strong invigoration effect for lower base clouds indicated by great increases of cloud thickness causes the increase of rainfall frequency as the CN number concentration increases. The change of cloud thickness in summer only also shows the same result.

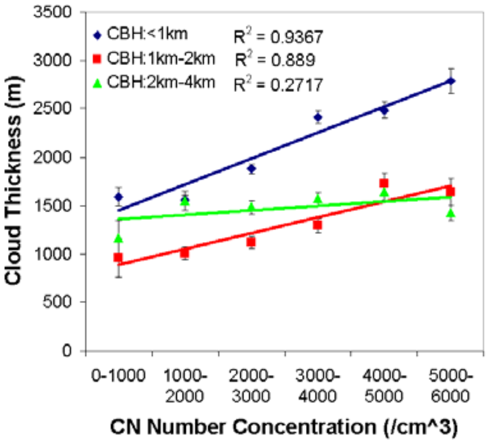

Figure 3. Cloud thickness as functions of CN number concentration for clouds with different base heights in all seasons. The error bars correspond to the standard errors of the averaged cloud thickness.

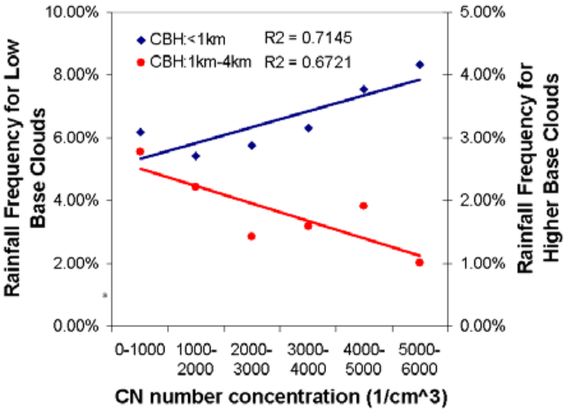

Figure 4. Rainfall frequency as functions of CN number concentration for clouds with different base heights in all seasons.

5. COMPETING WITH AEROSOL RAIN SUPPRESSION EFFECTS

While the increase of cloud thickness with CN presents a compelling evidence in support of the invigoration effect, the rainfall frequency only increases for lower base clouds, but deceases for higher base clouds with increasing CN number concentration. This implies there are effects offsetting the invigoration effect, leading to different responses of rainfall frequency to the increase of CN number concentration. We hypothesize that this effect is the aerosol indirect effect which reduces cloud particle size and suppress rainfall by competing available water vapor and weakening collision and coalescence processes. This effect can compete with the invigoration effect and which one is dominant may determine how the rainfall frequency changes.

To prove this, we derive a conceptual equation that may explain the responses of rainfall frequency to the changes of CN number concentration. Rigorously, rainfall frequency can hardly be expressed as a function of other variables due to very complicated physical and dynamic processes. However, in light of the fact that rain occurs only when large cloud drops are present, we may use cloud effective radius as a proxy of rainfall frequency to demonstrate the competition of the two effects. Since cloud droplet number concentration (N_c) is a power-law function of column aerosol number concentration (N_a) [*Nakajima et al.*, 2000], cloud effective radius (R_e) can be expressed as:

$$\mathrm{R}_e = \sigma N_a^{-\alpha} H^{\beta} \qquad (1)$$

where H is the cloud thickness, σ , α and β are coefficients. The two exponents reflect the importance of CN and cloud depth in determining cloud drop size respectively [*Shao and Liu*, 2005]. This equation implies that the cloud effective radius is determined by two independent factors: the aerosol indirect effects and the cloud geometrical thickness and the latter is related to the aerosol invigoration effect here. Based on previous study [*Brenguier et al.*, 2003] and the relationship between H and N_a in this study, H can be parameterized as:

$$H = A N_a^{B} \qquad (2)$$

where A and B are constants. Combining (1) and (2) yields an exponential dependence of the cloud effective radius R_e on aerosol number concentration N_a :

$$\mathrm{R}_e = C N_a^{B\beta-\alpha} \qquad (3)$$

where C = σA^{β} . C may be different for different relations between H and N_a .

Eq. 3 shows that the cloud effective radius can be approximated by a combination of two effects: aerosol indirect effect and invigoration effect which are controlled by -α and Bβ , respectively. The dependence of cloud effective radius on the change of CN number concentration is determined by their combined effect. Using this conceptual model, Figure 5 demonstrates the competition of the two effects. Three different regimes B$\beta > \alpha$, B$\beta = \alpha$, and B$\beta < \alpha$ results in three different conditions: strong, moderate, and weak invigoration effects. When B $\beta < \alpha$, the aerosol indirect effect dominates and R_e decreases with increasing aerosol number concentration. However, when B$\beta > \alpha$, dynamic effects overtake the microphysical effect and R_e increases with the increase of N_a . R_e is neutral if these two effects are in balance. This model results resemble the pattern of observational data as shown in Figure 1 and may thus explain the responses of rainfall frequency to the changes of CN concentration as shown before.

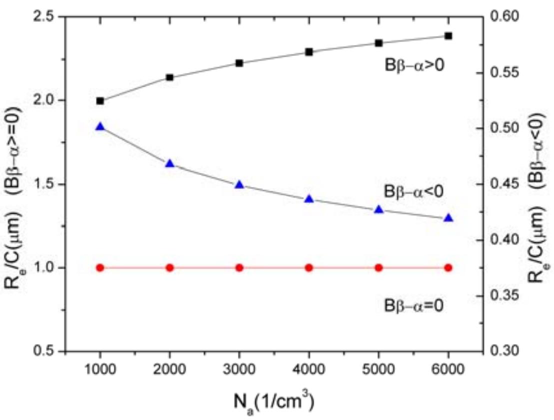

Figure 5. Conceptual model demonstrating the competition of aerosol indirect and invigoration effects as expressed by Eq. 3.

Since the invigoration effect is very strong for low base clouds but weak for high base clouds, it is expected to observe distinct behaviors of cloud effective radius as a function of CN concentration. To find such an evidence, we used Moderate Resolution Imaging Spectroradiometer (MODIS) retrievals of cloud effective radius over SGP site to test different responses of cloud effective radius. The MODIS retrievals of cloud effective radius were co-located with ground-based observations of CN number concentration. The relationships between cloud effective radius and CN number concentration were drawn for low base clouds (CBH<1km) and high base clouds (1km<CBH<4km). Results show that the cloud effective radius slightly increases with the increase of CN concentration for low base clouds (cloud base<1km) but decreases for higher base clouds (1km<cloud base<4km). This result indicates that when the invigoration effect is strong enough for low base clouds as shown in Figure 5, it may outweigh the rain suppression effect to increase cloud effective radius through the increase of cloud thickness. However, when the invigoration effect is weak for higher base clouds, the indirect effect becomes dominant and the rain suppression effect shows up.

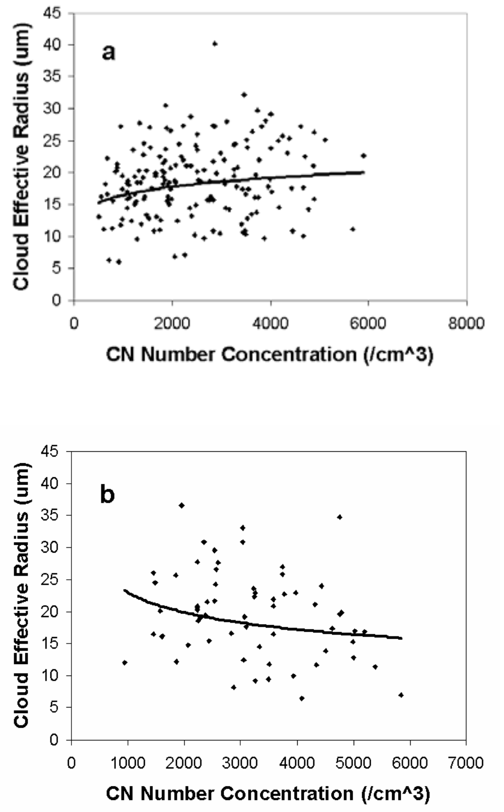

Figure 6. Relations between cloud effective radius and CN number concentration for clouds with low (a) and high (b) bases. The solid lines are power regression lines.

6. CONCLUSION AND DISCUSSION

The findings in this paper provide direct evidences of the aerosol invigoration effect. Cloud thickness was found to increase with CN number concentration for lower base clouds. The increase of cloud thickness leads to higher rainfall frequency.

More importantly, the invigoration effect may compete with aerosol rain suppression effect. The relative strength of these two effects determines how rainfall frequency responses to the change of aerosols. Cloud base height plays a key role in determining the balance of these two effects. Low base clouds have strong invigoration effect that exceeds the aerosol rain suppression effect, leading to larger cloud effective radius and enhancement of rainfall. Conversely, high base clouds usually have weak invigoration effect and the rainfall is suppressed by reducing cloud effective radius by aerosols. A theoretical explanation of the competition of these two effects was provided. The complex responses of rainfall frequency to the increase of CN number concentration can be quanlitatively explained by the theoretical model. A simple test using MODIS data supported such explanation. Since the aerosol invigoration effect may greatly change cloud properties, aerosol indirect effects studies especially those based on satellite observations need to account for the invigoration effects.

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