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<th>Effect of precipitation on water cloud properties over China</th>
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Abstract

I compared the amount of precipitation $P$ and non-precipitation water cloud properties (effective radius $r_e$ and columnar number density $N_c$ of droplets) over China in the mid-latitude frontal zone. In general, $N_c$ decreased and $r_e$ increased as $P$ increased. The rates of variation also became less steep beyond a certain $P$ for both parameters, suggesting saturation. These relationships could be interpreted as due to the effect of scavenging of aerosols via precipitation on the cloud properties. The observed cloud properties of fewer cloud condensation nuclei (CCN) in the rain-rich regions and of more CCN in the rain-poor regions support a previously proposed mechanism. Comparison with an Amazon case in the convective zone revealed some similarities and differences in the characteristics of the obtained relationships.

1. Introduction

Cloud-relevant phenomena such as the indirect effects of aerosols are quite uncertain in future climate projections by general circulation models (GCM). There are two kinds of indirect aerosol effect. In the first kind, an increase in aerosols which serve as cloud condensation nuclei (CCN), leads to a decrease in the droplet size and an increase in the optical depth of clouds. This is the well-known Twomey effect [Twomey 1977]. In the second kind, aerosols decrease the size of cloud droplets, reducing the efficiency of precipitation formation and increasing the fractional cloudiness [Albrecht 1989]. This second kind is particularly thought to be one of the most uncertain processes in the climate system [IPCC 2007].

Several observational studies of aerosols and low-level water clouds at various spatial scales have investigated the Twomey effect. For example, Nakajima et al. [2001] used Advanced Very High Resolution Radiometer (AVHRR) data to perform the first measurements of aerosol–cloud relationships over the global ocean. Breon et al. [2002] made similar global analyses over both land and ocean using Polarization and Directionality of the Earth’s Reflectances (POLDER) data.
Feingold et al. [2003] investigated the variation in cloud droplet particle sizes with aerosol extinction using ground-based instruments in Colorado, USA. Kawamoto et al. [2006] examined the behavior of satellite-derived cloud properties and model-calculated amounts of aerosols over China.

The effect of aerosols on precipitation has been also investigated. Rosenfeld [2000] used the Tropical Rainfall Measuring Mission (TRMM) to demonstrate that urban and industrial air pollution could reduce the cloud particle size and suppress precipitation off the Australian coast. Also, Rosenfeld [2007] proposed inverse relations between the amounts of aerosols and orographic precipitation in the central China. These results are consistent with the findings of Albrecht [1989].

The influence of precipitation on cloud behavior is another important topic that has received less attention thus far. Kawamoto and Nakajima [2003] observed differences in the cloud particle size between rainy and dry seasons using long-term satellite retrievals. Kawamoto [2006] then analyzed the relationship between precipitation and non-precipitation low-level water cloud properties (namely the size and number density of droplets) over the Amazon basin, where convective severe rainfall events are characteristic in the rainy season (January to March). Investigating the behavior of clouds with different kinds of atmospheric particles, i.e., aerosols and raindrops varying in size by several orders from approximately $10^{-8}$ to $10^{-3}$ m, Kawamoto [2006] found a correlation between the amount of precipitation and particle size and an anti-correlation between the amount of precipitation and the columnar cloud droplet number density. These findings were interpreted as possible links of the precipitation scavenging of aerosols and the Twomey effect.

I examined these relationships between precipitation and non-precipitation low-level water cloud properties in the mid-latitude frontal zone and compared them with a convective case of Amazon. I chose the central part of China (106°–123° E, 35°–45° N) as the region of this study. I limited the area analyzed because several different climate regimes occur over the whole of China, and the mixing of climate characteristics complicates such an analysis. The so-called ‘cold rain’ process, in which differences in the saturation vapor pressure cause ice crystals to grow more rapidly through the evaporation of supercooled water, is dominant at mid-latitudes.

2. Data

I used the following precipitation and low-level water cloud products. For the monthly amount of precipitation $P$, I used the Climate Prediction Center (CPC) Merged Analysis of
Precipitation (CMAP, see Xie et al. [2007] for details) dataset, which was created by the method of Xie and Arkin [1996]. The merging algorithm utilized ground-based rain gauge observations, satellite estimates derived from outgoing longwave radiation and microwave sensors, and precipitation distributions from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis dataset.

For low-level water clouds in which top temperatures were warmer than 273 K, the algorithm of Kawamoto et al. [2001] was used to retrieve microphysical properties, such as the optical depth $\tau_c$ and effective particle radius $r_e$. This algorithm is based on the principle that the solar reflection at a non-absorbing visible wavelength depends on $\tau_c$, whereas the solar reflection at a water-absorbing near-infrared wavelength is sensitive to $r_e$ [Nakajima and Nakajima 1995]. The algorithm was applied to AVHRR data to obtain $0.5^\circ$ (latitude/longitude) monthly mean values (January, April, July, and October) for $\tau_c$ and $r_e$ from daily orbit data. I used data from July only (the rainy season over the target region) in 1993. Although four months (i.e., January, April, July and October) of analyses were performed for cloud retrievals, a sufficient number of samples could be obtained only for July from the following reasons: 1) fewer water clouds occurred in the other months, and 2) the algorithm of Kawamoto et al. [2001] did not perform retrievals when solar zenith angles were larger than $70^\circ$ due to decreased accuracy of the results. The year 1993 was adopted for the purpose of comparison with the Amazon case studied by Kawamoto [2006]. The columnar cloud droplet number density $N_c$ was converted from $\tau_c$ and $r_e$ by assuming vertical homogeneity of the cloud layer [Nakajima et al. 2001]. The spatial and temporal resolutions were $0.5^\circ$ (latitude/longitude) and monthly, respectively, for all data used in this study.

Some previous studies have distinguished precipitation clouds from non-precipitation clouds using cloud properties. Nauss and Kokhanovsky [2006] reported that the probability of rainfall over mid-latitudes would be < 10% when $\tau_c < \sim 20$ and $r_e < \sim 15 \mu m$, based on the $\tau_c$-$r_e$ diagram. Rosenfeld and Gutman [1994] used 14 $\mu m$ as the $r_e$ threshold for the association of drizzle and/or precipitation. However, Kawamoto et al. [2001] demonstrated from the altitude dependence of $r_e$ that the droplets of lower clouds were smaller and larger in number than those of middle clouds. This would reflect the vertical profile of aerosol abundance, which indicates that more aerosols exist in the lower part of the atmosphere, particularly over land. Considering the results of these studies, I only used clouds with $\tau_c < 20$, $r_e < 14 \mu m$, and top heights < 2.5 km to examine the effects of $P$ on low-level non-precipitation clouds.

3. Results
Overall geographical characteristics of $P$ and cloud properties have been described by Xie et al. [2007] and Kawamoto et al. [2006], respectively. The relationships between precipitation and cloud properties were examined using the following procedure. The $P$ was divided into several bins, and cloud properties in the same geographical grid were collected for each $P$ bin. The average and standard deviation of cloud parameters for each $P$ bin are noted in all the figures below. Nakajima et al. [2001] and Kawamoto [2006] used this same method to examine relationships between relevant parameters. As stated in Section 2, the spatial and temporal resolutions of the datasets used in this study were 0.5° and monthly, respectively. At such resolutions, complete correspondence of analyzed clouds occurring immediately after the precipitation and being located in exactly the same place would not be warranted. Nonetheless, the primary purpose of this study was to describe the overall relationships between both parameters. Some other studies also used this methodology [e.g., Nakajima et al. 2001, Breon et al. 2002, Kawamoto 2006].

Values of $r_e$ and $N_c$ were generally correlated and anti-correlated with $P$, respectively (Fig. 1). In both cases, the rate of variation of $r_e$ and $N_c$ became less steep after $P$ reached approximately 150 mm/month. Applying the statistical test, variations up to the fifth $P$ bin (143 mm/month) were judged significant (level of significance $p < 0.05$) for both $r_e$ and $N_c$. However, those after the sixth $P$ bin (more than 173 mm/month) were not significant. Values of $r_e$ and $N_c$ changed on average by approximately 2.2 µm and $2.7 \times 10^6$ cm$^{-2}$, respectively, from less rain region ($P$ bin of 20 mm/month) to more rain region ($P$ bin larger than 173 mm/month). Variations of $r_e$ and $N_c$ could be regressed linearly within the statistically significant part (from the first to fifth bins) for $r_e = 6.75 + 0.017P$, $N_c = 6.6 \times 10^6 - 18580P$. These responses could be interpreted as follows. Rain-rich regions (e.g., $P$ greater than approximately 200 mm/month) indicated aerosol-poor clean conditions because aerosols were scavenged from the atmosphere, resulting in lower $N_c$. Cloud droplets could grow larger in such CCN-sparse conditions. Moreover, the precipitation and related moist air would have provided sufficient water vapor for the growth of cloud particles. The reduction in the rate of variation after $P$ reached approximately 150 mm/month may have been caused by the saturation of the response. Rain-poor regions ($P < 80$ mm/month) would have contained more aerosols because of the decrease in scavenging efficiency. There, $N_c$ would have been higher, and cloud droplet growth would have been limited because of the scarcity of available water vapor. Among possible interpretations, this idea would suggest the unilateral effects of precipitation on low cloud properties and is consistent with an interpretation by Kawamoto [2006].
An examination of the $\tau_a$ variation with $P$ would strengthen the above interpretation. Aerosol optical depth ($\tau_a$) was an appropriate parameter for this purpose. The Total Ozone Mapping Spectrometer (TOMS) was the only instrument from which global-scale $\tau_a$ retrievals, especially retrievals over land, for about 20 years from the late 1970s were available [Torres et al. 2002]. There was an anti-correlation between $P$ and $\tau_a$ in July 1992 (Fig. 2), clearly showing the precipitation scavenging of aerosols. Values of $\tau_a$ in rain-poor regions (less than the third $P$ bin of 81 mm/month) were statistically determined to be significantly larger ($p < 0.05$) than those in rain-rich regions (more than the seventh $P$ bin of 206 mm/month). Unfortunately, because the operation of TOMS failed between May 1993 and July 1996, I could not examine data that were concurrent with those in my analyses. However, anti-correlations between $P$ and $\tau_a$ were also found in other years. The same thresholds of $\tau_a < 20$, $r_e < 14$ µm, and top heights < 2.5 km were applied to the satellite data for clouds over Amazon (70°–50° W, EQ–15° S) in January 1993 (the rainy season), and the results from the central China and Amazon were compared.

The overall tendencies were the same for both cases: a correlation between $P$ and $r_e$ (Fig. 3), an anti-correlation between $P$ and $N_c$ (Fig. 4), and saturation beyond a certain $P$ value. The statistical test indicated that variations until the fourth $P$ bin (185 mm/month) were significant ($p < 0.05$) for both $r_e$ and $N_c$. However, those after the fifth $P$ bin (215 mm/month) were not significant. Values of $r_e$ and $N_c$ changed on average by approximately 1.7 µm and $1.4 \times 10^6$ cm$^{-2}$, respectively, from the less rain region ($P$ bin of 95 mm/month) to the more rain region (larger than the $P$ bin of 215 mm/month) over Amazon. Variations of $r_e$ and $N_c$ could be regressed linearly within the statistically significant part (from the first to fifth bins) for $r_e = 5.88 + 0.018P$, $N_c = 4.6 \times 10^6 - 15443P$. Hence, although general features of the variations can be considered common to low water clouds in both convective and frontal precipitation systems, some differences were also found. As for $r_e$, rates of variations up to the saturation points and absolute values in the rain-rich regions were almost the same, but $P$ values of the saturation points were slightly different over China and Amazon cases. For $N_c$, rates of variations up to the saturation points, absolute values in the rain-rich regions and $P$ values of the saturation points were somewhat different over both cases. These results appear to indicate the importance of processes other than precipitation in controlling cloud properties and behavior. Differences in the background CCN number density and ambient air conditions (e.g., updraft velocity and temperature and humidity profiles) all likely contribute to differences in cloud properties. Although I checked the relationship between $P$ and $\tau_a$ over Amazon, distinct differences with the China case could not be found, probably due to a number of missing data. Aerosol retrievals require clear sky conditions, which are difficult to meet given the large footprints of the TOMS
instrument. A calculation of the quantitative dependence of saturation points and rates of variation on these variables is beyond the scope of the current work. For this, a collaborative numerical modeling study of cloud physics would be extremely beneficial.

4. Conclusions

I analyzed the monthly variations in $P$ (obtained by the merged method), $r_c$, and $N_c$ (retrieved from satellite data) in July 1993 over China in the mid-latitude frontal zone. Comparative analyses generally showed that $r_c$ increased and $N_c$ decreased as $P$ increased. However, the rates of variation became less steep for both parameters after a certain $P$, suggesting saturation. One interpretation of these relationships is that in low water clouds, aerosols have a unilateral scavenging effect via precipitation. The behavior of low clouds with low CCN concentrations in rain-rich regions (i.e., those similar to oceanic clouds) and those with high CCN concentrations in rain-poor regions (i.e., those similar to continental clouds) was consistent with the mechanism proposed by Twomey [1977]. An examination of the $\tau_s$ variation with $P$, which showed an anti-correlated trend, strengthened this interpretation. Nevertheless, observed results never suggest causality between precipitation and cloud properties, only correlation. I interpreted the obtained relationships according to two widely accepted theories (aerosol scavenging by precipitation and the Twomey effect). Although the statistical significance was confirmed for $r_c$ and $N_c$ variations when $P$ was not so large, there were substantial scatters in the relationships examined here, implying that processes other than precipitation affect cloud behavior. Several processes are involved in the formation and maintenance of clouds, including dynamic (local updraft velocity and/or large-scale convection/subsidence), thermodynamic (temperature and humidity profiles), and particle effects (e.g., number, chemical composition, and size distribution of aerosols). For example, Kim et al. [2008] have recently highlighted the importance of mixing and entrainment processes in determining cloud optical properties, based on detailed ground-based measurements.

A comparison of my data from the central China region with similar data from the Amazon case indicated both similarities and differences. The overall tendencies of $P$ with the cloud properties were similar, but there were differences, particularly in the saturation points for the two regions. A numerical modeling approach is required to explain the quantitative differences in the rates and saturation points. My observational findings provide valuable constraints for numerical models that would help to validate any simulated results.

As stated above, the spatial and temporal resolutions of the datasets used in this study were 0.5° and monthly, respectively. Further observations at finer timescales such as daily or hourly
resolution would be an interesting extension to my study. For this purpose, monitoring from the Oklahoma site of the Atmospheric Radiation Measurement (ARM) program, where various instruments are in place, would be preferable to less frequent satellite observations.

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Figure captions.

Figure 1. The relationships of $r_e$ and $N_c$ with $P$ over China.

Figure 2. The relationship of $\tau_a$ with $P$ over China.
Figure 3. The relationship of $r_e$ with $P$ over China and Amazon.

Figure 4. The relationship of $N_c$ with $P$ over China and Amazon.