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Characteristics of Droplet Size Distributions in Low-Level Stratiform Clouds Observed from Tokyo Skytree

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Abstract

Continuous observations of cloud droplet size distributions (DSDs) in low-level stratiform clouds have been conducted at a height of 458 m from Tokyo Skytree (a 634-m high broadcasting tower in Tokyo) using a cloud droplet spectrometer. In this report, the characteristics of cloud parameters related to the cloud DSD from June to December 2016 are presented. The mean cloud droplet number concentration ($N_c$), average diameters, and effective diameters of cloud droplets in non-drizzling clouds were 213 cm$^{-3}$, 7.3 μm, and 9.5 μm, respectively, which are close to the reported values for continental stratiform clouds. The relationship between the liquid water content (LWC; g m$^{-3}$), $N_c$ (cm$^{-3}$) and radar reflectivity ($Z$; mm$^6$ m$^{-3}$) was estimated as $LWC = 0.17 N_c^{0.50} Z^{0.45}$, with a coefficient of determination ($R^2$) of 0.93. The observed cloud DSDs were well fitted by a lognormal distribution and the average median diameter of the fitted DSD was 6.6 μm.

Keywords cloud droplet, stratiform cloud, Tokyo Skytree
1. Introduction

The cloud droplet size distribution (DSD) is an important factor that influences precipitation processes and the optical properties of clouds. For example, the width of the DSD spectra strongly affects the efficiency of raindrop formation in liquid-phase clouds (Berry and Reinhardt 1974), and the optical thickness of clouds can be characterized as a function of the cloud DSD (Twomey 1977). Therefore, observation of the DSD is essential for understanding the precipitation process and the optical properties of clouds.

It is well known that the features of cloud DSDs differ greatly by geographical region. Over the ocean, where the number of aerosol particles is relatively low, the mean diameter of cloud droplets tends to be bigger than over continents, where aerosol particles are abundant (e.g., Miles et al. 2000). The Japan Islands are located between the Eurasian continent and the Pacific Ocean, and are thus interesting region to study the cloud DSD since they are affected by air masses of both continental and oceanic origin.

Observations of the cloud DSD around Japan have been conducted mainly for stratocumulus clouds developing over the East China Sea and the Sea of Japan because of their importance to the global climate (Ichimura et al. 1980; Harimaya et al. 2004; Nakajima et al. 2005; Adhikari et al. 2005; Koike et al. 2012). In these observations, the number concentration of cloud droplets ($N_c$) ranged from about 100 to 1000 cm$^{-3}$. These values are not far from those of cumulus clouds in summer on the Pacific coast of Japan (Kochi City) where $N_c$ ranged from 400 to 1500 cm$^{-3}$ (Murakami et al. 2014). These
observations suggest that the characteristics of the cloud DSD around Japan are similar to those of continental clouds that are characterized by high $N_c$. These data were obtained from observations conducted over short periods; however, it is necessary to acquire data over longer periods to elucidate the climatological features of the cloud DSD around Japan.

Currently, Tokyo Skytree (Fig. 1a), at a height of 634 m, is the tallest broadcasting tower in the world and was opened to the public in May 2012. The upper part of the tower is often covered with low-level clouds on humid days. Therefore, it is an ideal site to perform long-term observations of low-level clouds. Moreover, since it stands near the center of the metropolitan area, it can be used as a monitoring site of clouds affected by anthropogenic aerosol particles. Therefore, we installed a cloud droplet spectrometer at a height of 458 m on the tower to observe the climatological features of the cloud DSD in Tokyo and to provide data for validation of the remote sensing of clouds, such as by cloud radars. In this paper, we report the averaged properties of the DSD in low-level clouds observed from June to December 2016. The time and altitude used in this study are in local standard time for Japan (LST; UTC + 9 hours) and the height above ground level (sea level + 2 m).

2. Instruments and data processing

2.1 Instruments

The DSDs were observed by a Fog Monitor (FM-120) manufactured by Droplet Measurement Technologies, Inc. This instrument is a kind of forward scattering...
spectrometer probe (FSSP) using a laser beam with a wavelength of 0.658 μm. An attached pump sucks ambient air at a rate of 1 m³ min⁻¹ and measures the droplet number concentration across 30 intervals for diameters from 2 to 50 μm using the forward scattering intensity of droplets. The Fog Monitor was installed on the western side of Tokyo Skytree at a height of 458 m (35.71°N, 139.81°E; Fig. 1c). The inlet of the Fog Monitor was fixed horizontally to face westward. Observations were taken every second and averaged across one-minute intervals for the analysis.

Because the Mie scattering intensity does not increase monotonically with the diameter of cloud droplets, an error is included in the measurements of the droplet size from the Fog Monitor. According to Spiegel et al. (2012), this error can result in an overestimation of approximately 2 μm of the modal diameter of the cloud DSD and produces false spikes in the spectra. However, such spikes were only infrequently observed in our DSD spectra when the one-minute averages were used. Another source of measurement error is the loss of cloud droplets. This error can occur during the sampling and transporting processes for cloud droplets from the inlet of the Fog Monitor. Spiegel et al. (2012) showed that the error is more significant for larger droplets; under calm conditions, about 40% of the droplets with a diameter of 20 μm are lost while the loss of droplets is less than 10 % at a diameter of 10 μm. In this study, the number of lost droplets was estimated by assuming the loss rate to increase linearly with droplet diameter, with a loss rate of 10% at 10 μm and 40% at 20 μm diameter. As a result, the average percentage of lost droplets for each
sample was 3.2%, since most of the observed cloud droplets were less than 10 μm in diameter. Thus, no correction was made for this error.

When cloud droplets coexist with drizzle particles or raindrops, the cloud DSD may be modified due to coalescence. Therefore, it is necessary to determine whether drizzle particles or raindrops coexist when studying the cloud DSD. To detect drizzle particles, a Meteorological Particle Spectrometer (MPS; Baumgardner et al. 2002) manufactured by Droplet Measurement Technologies Inc. was installed in the same location as the Fog Monitor. The MPS measures the diameter and the number of particles falling through a laser sheet with a width of 3.1 mm. The detectable particle size is between 50 μm and 3.1 mm in 50-μm intervals. In order to minimize the effects of the ambient wind on the measurement of particle numbers, the instrument was originally installed on a turn table attached to a wind vane to keep the laser sheet parallel to the wind direction. However, we removed the wind vane in our observations and fixed the laser sheet in a north-south orientation because of the restrictions of the observation site. Thus, the number concentration of drizzle particles measured by the MPS in this study could include large errors under windy conditions. Therefore, we used the MPS data only to determine whether there were drizzle particles at the observation site, and not for estimating the DSD. As will be explained later, the MPS data were reliable for detecting drizzle. The data were averaged over one-minute intervals and converted to the radar reflectivity and smoothed with the 5-minute running mean.
As another way to detect drizzle particles, we used the radar reflectivity derived from the Ka-band radar belonging to the National Research Institute for Earth Science and Disaster Resilience (Maesaka et al. 2015). It is a scanning Doppler radar with a wavelength of 8.6 mm and a beam width of 0.3°, and the maximum range for the observation distance is 30 km. The Ka-band radar was installed approximately 15 km south of Tokyo Skytree (Fig. 1c). From the Ka-band radar, the observation site at Tokyo Skytree is located at an azimuth of 11.3° and an elevation angle of 1.6° with a range of 14.4 km. Figure 2 shows an example of the radar reflectivity around Tokyo Skytree obtained by the Ka-band radar. Because the tower is a strong reflector for the radar beam, a cross-shaped area of strong reflectivity is formed around the tower. In order to avoid contamination by such beam reflection, we used the radar reflectivity averaged over the four rectangular regions denoted by A, B, C and D in Fig. 2. We interpolated the data obtained every three minutes to one-minute intervals. Attenuation of the radar reflectivity due to clouds and rain was not corrected.

For the detection of raindrops, we used the rainfall intensity at the surface obtained by the XRAIN (eXtended RAdar Information Network; Godo et al. 2014). The XRAIN is an X-band polarimetric radar network operated by the Ministry of Land, Infrastructure and Transport that provides the rainfall intensity at a horizontal resolution of 250 m at one-minute time intervals. For missing data in the XRAIN, we used another X-band polarimetric radar network called X-NET (Maki et al. 2005) by interpolating the 5-minute interval data.
2.2 Dataset

The analysis period in this study is from 10:37 LST on 3 June to 23:59 LST on 31 December 2016. We have continuously recorded the DSD data during this period with the Fog Monitor except for during a few hours of maintenance. However, the MPS was not operational before 14:16 LST on 12 September 2016 due to mechanical trouble, and the Ka-band radar was not operated after 7:30 LST on 5 November 2016. Therefore, we used the Ka-band radar for drizzle detection before 12 September and used the MPS data afterwards.

We classified all DSD data into five categories: “RN” when it rained, “DZ” when it drizzled, “CL” for non-raining and non-drizzling clouds, “NC” for no clouds and “UC” for unclassifiable due to missing data. When the rainfall intensity derived from the XRAIN was greater than 0.1 mm h\(^{-1}\), we classified the data as “RN”. Otherwise, when the radar reflectivity derived from the MPS or the Ka-band radar was greater than -18.1 dBZ, we classified the data as “DZ”. Here the threshold value of -18.1 dBZ corresponds to the situation when one droplet with a diameter of 50 μm exists in a volume of 1 cm\(^3\). A droplet diameter of 50 μm is widely used as a threshold for drizzling clouds (e.g., Miles et al. 2000). The radar reflectivity used for the threshold for detecting drizzle was calculated from the MPS data or the Ka-band radar data. The ability to detect drizzle particles was compared when both the MPS and the Ka-band radar were available. Only 4.2% of the results were
different between the MPS and the Ka-band radar. Therefore, we consider that they have an approximately equivalent accuracy for drizzle detection.

Even when there were no clouds at the observation site, the Fog Monitor sometimes identified large aerosol particles as cloud droplets. In order to remove such noise, we classified the data as “CL” only when the liquid water content (LWC) was $> 0.01 \text{ g m}^{-3}$ in non-drizzling and non-raining clouds. Otherwise the data were classified as “NC”. When we could not classify the data due to missing values, the data were labeled as “UC”.

The dataset includes observation times (every minute), categories, $N_c \text{ (cm}^{-3}\text{)}, \text{LWC (g m}^{-3}\text{)},$ and $N_e$ in each size bin (cm$^{-3}$). In the dataset, 75.6% of observations were classified as “NC”, 7.1% were “UC”, 9.1% were as “DZ”, 5.7% were “RN”, and 1.8% were “CL”. The dataset is available from http://mizu.bosai.go.jp/wiki2/wiki.cgi?page=Tokyo_Skytree. In this report, we analyzed the 5511 observations classified as “CL” to describe the average characteristics of the DSD in non-drizzling and non-raining clouds. The results were compared with the DSD in low-level clouds observed at many places around the world as summarized in Miles et al. (2000).

2.3 Calculation of cloud parameters

The parameters related to the cloud DSDs were calculated from the Fog Monitor data by the following methods. In general, the $n$th-order moment, $M_n$, of a density function $n(D)$ is defined as:
\[ M_n = \int_0^\infty D^n n(D) dD, \]

where \( n(D) \) is the number concentration of droplets with diameters between \( D \) and \( D + dD \).

The values measured by the Fog Monitor are not \( n(D) \) but the number concentration of the droplets in the \( i \)th bin, \( N_i \). Therefore, we calculated \( M_n \) as:

\[ M_n = \sum_{i=1}^{i_{\text{max}}} D_i^n N_i, \]

where \( i_{\text{max}} \) is the maximum bin size of the Fog Monitor and \( D_i \) is the mean diameter of the \( i \)th bin. From (1), \( N_c \), LWC, the mean diameter \( (D_m) \) and the effective diameter \( (D_e) \) of cloud droplets, and radar reflectivity \( (Z) \) are obtained as:

\[ N_c = M_0, \]
\[ \text{LWC} = \frac{\pi}{6} \rho_w M_3, \]
\[ D_m = \frac{M_1}{M_0}, \]
\[ D_e = \frac{M_3}{M_2}, \]

and

\[ Z = M_6, \]

where \( \rho_w \) is the density of water. The standard deviation of the droplet diameters, \( \sigma_v \), which reflects the spectral width of the DSDs is given as:

\[ \sigma_v = \left( \sum_{i=1}^{i_{\text{max}}} \frac{N_i (D_i - D_m)^2}{N_c} \right)^{1/2}. \]

It is convenient to characterize the DSDs by fitting the data to an appropriate distribution. In this study, we used a log-normal distribution to model the observed DSDs.
as:

\[ n(D) = \frac{N_c}{\sqrt{2\pi}\sigma_{\log}D} \exp\left\{ -\frac{[\ln(D/D_{\log})]^2}{2\sigma_{\log}^2} \right\}, \] (9)

where \( D_{\log} \) is the median diameter of \( n(D) \) and \( \sigma_{\log} \) is a parameter related to the width of the DSD spectra. When the DSD is approximated by Eq. (9), \( M_n \) is then:

\[ M_n = N_c D_{\log} n \exp\left( \frac{1}{2} n^2 \sigma_{\log}^2 \right). \] (10)

From Eq. (10), the parameters \( D_{\log} \) and \( \sigma_{\log} \) are calculated in terms of \( M_0, M_3, \) and \( M_6 \) as:

\[ \sigma_{\log} = \sqrt[9]{\ln\left( \frac{M_0}{M_6} \right)} \] (11)

and

\[ D_{\log} = \sqrt[9]{\ln\left( \frac{M_3}{M_0 \exp\left( \frac{9}{2} \sigma_{\log}^2 \right)} \right)} \] (12)

From Eqs. (11) and (12), we can fit Eq. (10) to the observed DSD using the values of \( M_0, M_3 \) and \( M_6 \) which are proportional to \( N_c, LWC \) and \( Z, \) respectively.

3. Results

3.1 Cloud parameters

According to the frequency distribution of the data categorized as CL versus months and local times (figure not shown), the CL category, that is, non-raining/non-drizzling clouds, occurred at the observation site more frequently in the wet season (from June to October) than in the dry season (November and December). The occurrence of CL is also strongly
dependent on the local time; it appeared more frequently at night and in the early morning than in the daytime. Such diurnal variation is a typical feature of stratiform clouds formed at the top of the boundary layer (e.g., Oliver et al. 1978).

The observed values of $N_c$, $D_m$, $D_e$, and $\sigma_v$ versus LWC in the CL data are plotted in Fig. 3. For comparison, the corresponding values of continental (white circles) and marine low-level clouds (black spots), as presented in Miles et al. (2000), are shown. The maximum value of LWC observed at Tokyo Skytree is 0.44 g m$^{-3}$, while many of the LWC data in Miles et al. (2000) exceed 0.5 g m$^{-3}$. This is because our observation site is fixed at a height of 458 m, which roughly corresponds to the height of the cloud base, while the data in Miles et al. (2000) include higher-level observations by aircrafts. In general, $N_c$ does not vary greatly with height once the cloud droplets were activated near the cloud base, while LWC increases with height (Rogers and Yau 1989). Therefore, we consider that the $N_c$ observed at the Tokyo Skytree represents typical values of low-level clouds in Tokyo even though the observation site is fixed near the cloud base.

The values of observed $N_c$ were in the range from 7 to 1816 cm$^{-3}$, and many of them overlapped with those of the continental clouds of Miles et al. (2000) (Fig. 3a). More specifically, the average value and the standard deviation of $N_c$ were 213 cm$^{-3}$ and 177 cm$^{-3}$, respectively, which are close to the values in continental low-level clouds (see Table 1), although some observed $N_c$ were similar to marine clouds (Fig. 3a). The average values of $D_m$, $D_e$, and $\sigma_v$ were also similar to those in continental low-level clouds whose LWCs are in
a similar range to those observed from Tokyo Skytree (the fourth and fifth columns in Table 1).

3.2 Features of DSD

Figure 4a shows the droplet spectrum averaged for all of the CL data with the 95th and 5th percentile values. The averaged $n(D)$ has a modal diameter at $D = 6.5 \, \mu m$. To investigate the frequency distribution of modal diameters, we conducted the following analysis. First, we smoothed each observed $n(D)$ with the three-point moving average. Then, we defined a “modal diameter” when the sign of $dn(D)/dD$ changed from positive to negative where $n(D)$ was greater than $1 \, cm^{-3} \, \mu m^{-1}$. As a result, we found 90.7% of the cloud DSD spectra had a modal diameter between 5 and 8 \mu m. Only 0.8% had a bimodal DSD spectrum with the second modal diameter between 5 and 22 \mu m.

We fitted Eq. (9) to the observed DSDs and estimated the parameters $\sigma_{log}$ and $D_{log}$ using Eq. (10) and Eq. (11). Examples of two DSDs fitted to Eq. (10) are shown in Fig. 4b.

For the case where $N_c$ is extremely large (1810 cm$^{-3}$), the DSD is fitted to the curve with $D_{log} = 5.4 \, \mu m$ and $\sigma_{log} = 0.41$. On the other hand, for the case when $N_c$ is relatively small (167 cm$^{-3}$), the parameters are $D_{log} = 13.4 \, \mu m$ and $\sigma_{log} = 0.33$. The curves well reproduce the difference of the median diameters ($D_{log}$) in these cases, although they deviate slightly from the observed values for $D > 20 \, \mu m$. The averaged $D_{log}$ was close to that for continental low-level clouds in Miles et al. (2000), and $\sigma_{log}$ was identical to those for continental and
3.3 Empirical relationships among $N_c$, LWC, and $Z$

When estimating cloud parameters by remote sensing, it is useful to discern if there is an empirical relationship between cloud parameters to help reduce the number of unknown variables. In the present study, we assumed the following relationship among $N_c$, LWC and $Z$:

$$\text{LWC} = \alpha N_c^\beta Z^\gamma.$$  \hspace{1cm} (13)

The parameters $\alpha$, $\beta$ and $\gamma$ were determined by fitting Eq. (13) to the observation data. As a result, the coefficient of determination ($R^2$) reached its maximum (0.93) when $\alpha = 0.17$, $\beta = 0.50$ and $\gamma = 0.45$ (Fig. 5a), where the units of $N_c$, LWC and $Z$ were cm$^{-3}$, g m$^{-3}$ and mm$^6$ m$^{-3}$, respectively. This empirical relationship was derived from the data in the ranges from 0.01 to 0.41 g m$^{-3}$ for LWC, from 7 to 1810 cm$^{-3}$ for $N_c$, and from -52.9 to -20.8 dBZ for the radar reflectivity.

The $Z$-LWC relationships are widely used to estimate LWC from cloud radars. In the present study, the relationship between $Z$ and LWC is very scattered (Fig. 5b), and a regression curve is given by

$$Z = 0.015\text{LWC}^{1.44}$$ \hspace{1cm} (14)

with $R^2 = 0.63$. The relationship shown in Eq. (14) is compared to previous ones obtained by a different method and with the observations (Fig. 5b): those theoretically derived by
Atlas (1954) \( Z = 0.048 \text{LWC}^2 \), and those derived from in situ observations over the Pyrenees by Sauvageot and Omar (1987) \( Z = 0.047 \text{LWC}^{1.83} \) and from in situ observations over the North Atlantic and around the British Isles by Fox and Illingworth (1997) \( Z = 0.031 \text{LWC}^{1.56} \). The relationship given in Eq. (14) is close to those in the other studies when \( \text{LWC} < 0.4 \text{ g m}^{-3} \), although the exponent in the right-hand side of Eq. (14) is slightly smaller than previous ones.

4. Summary

We installed a cloud droplet spectrometer at a height of 458 m on Tokyo Skytree and conducted a continuous observation of the cloud DSDs. According to the 5511 observations for non-raining/non-drizzling clouds obtained from June to December 2016, the average values of \( N_c \), \( D_m \) and \( D_e \) were 213 cm\(^{-3} \), 7.3 \( \mu \text{m} \) and 9.5 \( \mu \text{m} \), respectively. These values were very close to those for continental low-level clouds presented in Miles et al. (2000).

The empirical relationship for \( N_c \) (cm\(^{-3} \)), LWC (g m\(^{-3} \)) and \( Z \) (mm\(^6 \text{ m}^{-3} \)) was estimated as \( \text{LWC} = 0.17 N_c^{0.50} Z^{0.45} \) with \( R^2 = 0.93 \). Each DSD was well fitted by a lognormal distribution and the averaged median diameter of the fitted curves was 6.6 \( \mu \text{m} \).

In this paper we reported the average characteristics of parameters related to cloud DSD based on in-situ measurements on Tokyo Skytree from June to December 2016. Variations of cloud DSDs and their impacts on precipitation process will be discussed in a future paper. We have also observed the number concentration of cloud condensation
nuclei and ice nuclei, and the number-size distribution and biological origin of aerosols in the same location on Tokyo Skytree. The results will be reported in the near future.

Acknowledgments

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<table>
<thead>
<tr>
<th></th>
<th>Tokyo Skytree</th>
<th>Marine (LWC &lt; 0.124 g m$^{-3}$)</th>
<th>Continental (LWC &lt; 0.124 g m$^{-3}$)</th>
<th>Marine (LWC &lt; 0.124 g m$^{-3}$)</th>
<th>Continental (LWC &lt; 0.124 g m$^{-3}$)</th>
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</thead>
<tbody>
<tr>
<td>$N_c$ [cm$^{-3}$]</td>
<td>213 (177)</td>
<td>74 (45)</td>
<td>288 (159)</td>
<td>74 (70)</td>
<td>217 (182)</td>
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<td>$D_m$ [µm]</td>
<td>7.3 (1.5)</td>
<td>14.2 (3.4)</td>
<td>8.2 (3.9)</td>
<td>10.8 (4.0)</td>
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<td>$\sigma_v$ [µm]</td>
<td>2.5 (1.1)</td>
<td>5.8 (2.0)</td>
<td>3.1 (1.2)</td>
<td>4.8 (2.0)</td>
<td>3.0 (2.1)</td>
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<tr>
<td>LWC [g m$^{-3}$]</td>
<td>0.064 (0.060)</td>
<td>0.18 (0.14)</td>
<td>0.19 (0.21)</td>
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<tr>
<td>$D_e$ [µm]</td>
<td>9.5 (2.9)</td>
<td>19.2 (4.7)</td>
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<td>15.4 (5.7)</td>
<td>9.7 (5.7)</td>
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<td>$\sigma_{\log}$</td>
<td>0.38 (0.08)</td>
<td>0.38 (0.13)</td>
<td>0.38 (0.14)</td>
<td>0.43 (0.14)</td>
<td>0.43 (0.15)</td>
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<tr>
<td>$D_{\log}$ [µm]</td>
<td>6.6 (1.6)</td>
<td>13.1 (3.6)</td>
<td>7.7 (3.8)</td>
<td>9.6 (4.0)</td>
<td>5.8 (2.8)</td>
</tr>
</tbody>
</table>