Comparison of water cloud microphysics over mid-latitude land and ocean using

CloudSat and MODIS observations

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ABSTRACT

The microphysical properties and processes of water (liquid-phase) clouds in the mid-latitudes were studied using space-borne radar and radiometer data, with a focus on comparisons between continental (over China) and oceanic (over the northwest Pacific) clouds. The probability distribution functions (PDFs) of cloud parameters were examined and found to be both reasonable and consistent with previous observations. The PDFs of oceanic cloud parameters as a function of radar reflectivity were generally better defined than those of land cloud parameters. Precipitation characteristics were categorized into non-precipitating, drizzle, and precipitating, as well as the total-precipitating category, according to the maximum radar reflectivity within the cloud layer. The fractional occurrence of the precipitation categories was analyzed as a function of the liquid water path. The statistics showed general trends that were very similar for both land and oceanic clouds, such as a monotonically decreasing trend for the non-precipitating category, a convex shape for the drizzle category, and a monotonically increasing trend for the precipitating and total-precipitating categories with increasing liquid water path. The fractional occurrence of the precipitation categories was further investigated as a function of multiple cloud parameters to better understand land–ocean contrasts in cloud development stages. The vertical structure of clouds also revealed that oceanic clouds produced heavier precipitation in optically thicker regions, compared to land clouds with fewer cloud droplets. However, the differences between land and oceanic clouds were small when comparisons included only those clouds with a high density of droplets.
1 Introduction

Clouds play a crucial role in Earth’s radiation budget. For example, small changes in cloud albedo, vertical distribution, and lifetimes can have a significant impact on the distribution of radiative heating around the globe [1]. Moreover, the various combinations of optical properties among clouds, aerosols, and water vapor create complicated effects on radiation processes [2]. In addition to the radiative effects, clouds also affect the water cycle through precipitation. It is therefore important to improve our understanding of the frequency and magnitude of precipitation in warm clouds [3].

These climatic effects of clouds are also complicated by their interactions with aerosols through the so-called aerosol indirect effect. An increase in the aerosol concentration acts to increase cloud condensation nuclei. The increased number of the condensation nuclei creates smaller and more numerous cloud droplets, which lead to higher cloud reflectivity when the liquid water content is fixed [4]. The decrease in the cloud droplet size also inhibits precipitation and consequently increases the cloud lifetime [5]. In addition, Hansen et al. [6] introduced the idea of the aerosol semi-direct effect in which radiative absorption by aerosols heats the surrounding atmosphere, causing atmospheric stratification that results in a reduction in cloud cover. Huang et al. [7] observationally found that the semi-direct effect of dust aerosols warmed clouds, increased the evaporation of cloud droplets and further reduced the cloud water path. The
interaction of aerosols and clouds through these mechanisms still remains one of the most uncertain processes in the climate system [8].

To overcome such a difficulty in understanding the cloud processes and their interaction with aerosols, observations of clouds are crucial. Among various observational tools, satellite-borne instruments are particularly promising for monitoring wide areas with high spatial and temporal resolutions. Passive radiometers, such as the Advanced Very High Resolution Radiometer (AVHRR), have retrieved important cloud microphysical data for several decades. Using these data, Han et al. [9] and Nakajima and Nakajima [10] completed near-global and wide-area analyses, respectively, measuring the cloud optical depth ($\tau_c$) and effective particle radius ($r_e$) with non-absorbing (0.6-µm) and water-absorbing (3.7-µm) channels. The subsequent Moderate Resolution Imaging Spectroradiometer (MODIS) extended retrieval capabilities, employing 36 channels from the ultraviolet to infrared wavelengths.

More recently, active remote sensing data have become available, such as those from the CloudSat satellite. Launched in April 2006, CloudSat carries the Cloud Profiling Radar (CPR), operating at 94 GHz. A synergetic approach using both active (e.g., CloudSat) and passive (e.g., MOSIS) instruments, such as in the A-Train satellite constellation [11], is an extremely powerful tool in revealing the detailed vertical droplet structures inside clouds, which were previously unknown. A method that combines the radar reflectivity ($Z_e$) inside the cloud layer from CloudSat with the $\tau_c$ of the whole cloud layer, as well as $r_e$ near the cloud top from MODIS, has been devised and used by several
previous studies. For example, Lebsock et al. [12] reported aerosol effects on $Z_e$, the liquid water path (LWP), and $r_e$ over global oceans. Suzuki and Stephens [13] found sixth-power and cubic relationships between $Z_e$ and the effective particle radius of oceanic clouds, illustrating that condensation and coagulation constituted the dominant particle-growth processes at smaller and larger $Z_e$ values, respectively. Furthermore, Nakajima et al. [14] and Suzuki et al. [15] devised a way of combining the vertical profile of $Z_e$ with $r_e$ values derived from MODIS 2.1-$\mu$m and 3.7-$\mu$m channels to examine particle-growth processes occurring within the cloud layer.

There have been, however, relatively few analyses of clouds over land, mainly owing to the more complicated surface conditions and the unavailability of microwave retrievals over land. Among the studies that have analyzed clouds over land, Kawamoto and Suzuki [16] (hereafter KS12) analyzed the microphysical transition of cloud particles into raindrops in single-layered water clouds over continental regions such as the Amazon and China. Their work was motivated by that of Kawamoto [17], who studied the relationship between cloud properties obtained from passive satellite remote sensing and precipitation rates collected by surface-based rain gauges. KS12 reported the fractional occurrence of precipitation categories defined with $Z_e$ as a function of the LWP, $\tau_c$ and $r_e$, behaviors according to precipitation categories, and the behavior of vertical cloud structures as dictated by the CloudSat radar profile information of $Z_e$.

As an extension from KS12 that was focused on continental clouds, the specific aim of the present study is to compare the properties and characteristics of land and
oceanic clouds in an attempt to identify the similarities and differences between them. For this purpose, we combined the observations from the active radar of CPR on-board CloudSat with those from the passive radiometer of MODIS on-board Aqua, in a manner similar to the study of KS12. We investigated several aspects of the cloud-to-precipitation transitional processes inside clouds over land (within 1000 km from 35°N and 105°W over China) and ocean (within 1000 km from 35°N and 165°E over the northwest Pacific) regions at mid-latitudes, which are indicated in Figure 1. These regions were chosen because they are adjacent and nearly continuous over the same latitudes, and therefore are suitable for the comparison analysis of land-ocean contrasts in mid-latitude water (liquid-phase) clouds. In this study, we confine our analyses to low-level water clouds because of their large area of coverage and substantial radiative effect. To avoid the complexity that arises from multi-layered clouds, we selected only single-layered clouds.

The remainder of this paper is arranged as follows. In Section 2, we briefly described the datasets used. Section 3 presented the main analyses conducted, specifically the probability distribution function (PDF) of cloud parameters, PDF of cloud parameters as a function of $Z_e$, the fractional occurrences of precipitation categories as a function of the LWP, the fractional occurrences of precipitation categories as a function of multiple cloud parameters in the context of their two-dimensional representations, and the transitional characteristics of cloud vertical structures as a function of $\tau_c$ and $Z_e$ according to the cloud droplet number density ($N_c$). Finally, Section 4 summarized the findings and conclusions of this study.
2 Datasets

We used the same five cloud parameters as used by KS12 to investigate the precipitation characteristics in clouds formed over land and ocean: $\tau_c$, $r_e$, LWP, $N_c$, and $Z_e$.

The $\tau_c$ and $r_e$ data were retrieved from the MODIS visible (non-absorbing) 0.6-µm and near-infrared (absorbing) 2.1-µm channels, and these values were taken from the CloudSat 2B-TAU product which only took MODIS pixels that were collocated with the CloudSat footprint [18]. This study used data with uncertainties less than 3 for $\tau_c$ and less than 1 µm for $r_e$. The LWP and $N_c$ values were derived from the $\tau_c$ and $r_e$ retrievals according to the adiabatic growth assumption: the LWP was calculated as $5\tau_c r_e/9$ [19] and $N_c$ was estimated using equation (1) below, which was originally equation (3) of Kubar et al. [20]:

$$N_c = \sqrt{2} B^3 \Gamma_{\text{eff}}^{1/2} \text{LWP}^{1/2} / r_e^3,$$

where $B = (3\pi \rho_w/4)^{1/3} = 0.0620$, $\rho_w$ is the density of liquid water, and $\Gamma_{\text{eff}}$ is the adiabatic rate of increase in the liquid water content with height. $\Gamma_{\text{eff}}$ is weakly dependent on pressure and temperature and was derived from a diagram by Wood [21]. Taking the uncertainties less than 3 for $\tau_c$ and less than 1 µm for $r_e$ into account, uncertainties of the inferred LWP and $N_c$ were generally estimated to less than 20 (g/m²) and 25 (1/cm³), respectively. $Z_e$ was obtained from the CloudSat 2B-GEOPROF product [22,23]. In addition, altitude and temperature profiles were obtained from the European Centre for
Medium-Range Weather Forecasts Auxiliary (ECMWF-AUX) dataset matched to the
CloudSat radar footprint [24].

We used the CloudSat data mentioned above, collocated with MODIS products
for the periods of June, July, August (JJA) and December, January, February (DJF) from
2006 to 2008, to examine the averaged behaviors of single-layered water clouds over
these seasons in mid-latitudes.

3. Results

3.1 Selection of single-layered water clouds

Only single-layered and water (liquid-phase) clouds having $\tau_c > 1$ and $r_e < 35$ (µm)
were selected to reduce retrieval error in the products. The single-layered requirement
was determined as follows, according to the method of Haynes and Stephens [25]. First,
moving upward from the lowest layer, i.e., the closest to the ground, we examined
whether layers met the following three conditions: (1) the cloud mask value was between
30 and 40; (2) $Z_e$ was not an undefined value; and (3) the height value was positive. The
first height bin that satisfied all of the conditions was defined as the cloud base. Next, we
examined the layers upward from the cloud base, and the bins that satisfied all of the
conditions were determined to be the cloud layer. The layer just under the first layer not
satisfying these conditions was defined as the “cloud top of the lower layer” (CTL). The
same procedure was then conducted downward from the highest layer, and the first layer that satisfied all the conditions was called the “cloud top of the higher layer” (CTH). If CTL and CTH were identical, we considered the cloud layer to be single-layered. Otherwise, we concluded that the atmospheric column consisted of multilayered clouds.

The latter (liquid-phase) requirement was identified by the CloudSat cloud mask criterion and an echo-top temperature warmer than 273K. We compared our cloud phase identification with the information of the 2B-CWC-RVOD product, which combined MODIS and CloudSat data. The results showed that 81.1% of our estimation of water agreed with the 2B-CWC-RVOD product over land and 75.2% agreed over ocean.

3.2 Probability distribution functions (PDFs) of cloud parameters

To investigate the overall characteristics of clouds, we first constructed PDFs of cloud parameters ($\tau_c$, $r_e$, LWP, $N_c$, and $Z_e$) over land and ocean, as shown in Fig. 2. Figure 2(a) shows that both land and oceanic clouds had a similar PDF of $\tau_c$, whose mode value was about 25, indicating that land clouds were slightly thicker optically. Figure 2(b) shows that oceanic clouds had distinctly larger $r_e$ than did land clouds and this difference was significant judging from the uncertainty of 1 µm considered in this study. Oceanic clouds had a higher mode value of the LWP than did land clouds, caused by larger values of $r_e$ (Figure 2(c)). Conversely, land clouds had definitely more $N_c$ than oceanic clouds (Figure 2(d)). This land–ocean contrast and the mode values of $N_c$ are reasonable and
comparable to results from past aircraft measurements (e.g., [26]). The land-ocean
contrast found in $N_c$ may reflect a signature in aerosol abundance, as supported by
MODIS-retrieved aerosol optical depth (AOD) annual-mean values [27], which were
estimated as 0.45 and 0.18 over land (characterized by industrial and dust aerosols) and
ocean (less influenced by anthropogenic sources), respectively. These features are also
those expected from the Twomey’s theory [4] and consistent with results of previous
observational studies (e.g., [28]). Also shown in Figure 2(e) is the PDF of $Z_e$ for all the
cloud layers. It was found that both land and oceanic clouds had bimodal characteristics,
and the mode value for oceanic clouds (roughly 2 dBZ) was larger than that of land
clouds (roughly -8 dBZ). Also, oceanic clouds showed a higher frequency of $Z_e > -5$ dBZ
than did land clouds, and vice versa. These features of land and oceanic clouds are similar
to those reported by KS12 for clouds over China and the Amazon, respectively.

For studying how these characteristics of cloud properties were related to
precipitation processes, the cloud-to-rain transition processes were analyzed in terms of
precipitation categories defined according to the maximum $Z_e$ value within the cloud layer.
The precipitation categories were defined with threshold values as follows: (i)
non-precipitating ($Z_e < -15$ dBZ); (ii) drizzle ($-15$ dBZ < $Z_e < 0$ dBZ), and (iii)
precipitating ($0$ dBZ < $Z_e$), following Suzuki et al. [29]. L’Ecuyer et al. [1] further divided
the drizzle category into two subcategories of drizzle ($-15$ dBZ < $Z_e < -7$ dBZ) and light
rain ($-7$ dBZ < $Z_e < 0$ dBZ), although that classification was not used here. In addition to
the three categories above, we also introduced the category of total-precipitating events
(-15 dBZ < $Z_e$) as combined category of the drizzle and precipitating categories defined above. These four categories are hereafter referred to as $Z_{e1}$, $Z_{e2}$, $Z_{e3}$, and $Z_{e4}$, respectively. The two threshold values of -15 and 0 dBZ dividing these categories were superimposed in Figure 2(e). Although Suzuki et al. [29] utilized near-surface non-attenuated radar reflectivity from the CloudSat 2C-PRECIP-COLUMN data available only over the ocean, we used the maximum radar reflectivity within the cloud layer for consistent analyses over both land and ocean.

3.3 PDFs of cloud parameters as a function of $Z_e$

Next, we analyzed the PDFs of cloud parameters as a function of $Z_e$ to examine how they tend to change with changing $Z_e$, taking $Z_e$ as the horizontal coordinate and the PDFs of cloud parameters as the vertical coordinate. Figures 3 (a)–(d) and 4 (a)–(d) illustrate the results over land and ocean for $\tau_c$, $r_e$, LWP, and $N_c$, respectively. First, the tendencies of oceanic cloud parameters showed generally better-defined relationships with $Z_e$ values, such as a negative relationship of $N_c$ and positive relationships of $\tau_c$, $r_e$, and LWP as $Z_e$ increased with saturation for $Z_e > 0$ dBZ. Land clouds showed the same tendencies, except for the flat variation in $\tau_c$, but the tendencies were particularly less distinct for $Z_e > 0$ dBZ. The less distinct tendencies of land cloud parameters for this region might be partly due to the small number of samples, as shown in Fig. 2(e).
It should be noted that the LWP and \( N_c \) are by-products and are not independent of \( \tau_c \) and \( r_e \). We used the LWP obtained from \( \tau_c \) and \( r_e \) in the present study for consistent analyses over both land and ocean. It would be of interest in future studies to apply the same procedure to microwave-derived LWP values, which would be independent of optical measurements, for a comparison of oceanic cloud behavior since the microwave retrievals are available only over the ocean.

3.4 Fractional occurrence of precipitation categories as a function of the LWP

We analyzed the fractional occurrences of the four categories (\( Z_{e1} \)–\( Z_{e4} \)) as a function of the LWP and the results are shown in Fig. 5. In this study, the fractional occurrence was calculated as the ratio of the number of samples that satisfied the condition to the total number of samples in the bin. Note that the PDF is not shown in Fig. 5(a)–(d), unlike in Fig. 2(a)–(e). Lebsock et al. [12] found that the probability of precipitation, defined as the fractional occurrence of precipitation events, increased monotonically with the LWP for oceanic clouds. In Fig. 5(a) through (d), the fractional occurrences of non-precipitating, drizzling, precipitating, and total-precipitating categories are shown as a function of the LWP for land and oceanic clouds. Figure 5(a) presents monotonically decreasing trends for both land and oceanic clouds in the non-precipitating category. Land clouds had higher frequencies of the non-precipitating category than oceanic clouds for LWP from 100 to 500 (g/m\(^2\)). At LWP > 500 (g/m\(^2\)), a
The majority of clouds were either drizzling or precipitating. For the drizzling category (Fig. 5(b)), convex shapes are found for both land and ocean clouds, but the peak LWP was considerably larger for land clouds (about 400 g/m²) than for oceanic clouds (about 200 g/m²); the smaller particle sizes over land may have resulted in the larger frequency of drizzle compared to the precipitating category (Fig. 5(c)) as argued below. In Fig. 5(c) showing the precipitating category, both land and ocean clouds have monotonically increasing trends, but higher frequencies are found over LWP from 100 to 650 (g/m²) for oceanic clouds than land clouds that tend to have larger LWP values for the precipitation frequency to reach the comparable value to oceanic clouds. At LWP > 650 (g/m²), all clouds approached unity. In addition, the total-precipitating category in Fig. 5(d) shows a monotonically increasing trend. Although in general the precipitation frequency was higher in oceanic clouds than land clouds, the clouds over both areas were precipitating at LWP > 500 (g/m²), consistent with the interpretation of Fig. 5(a) for the non-precipitating category.

These behaviors of land clouds tend to be similar to those previously found in polluted coastal areas (e.g., Asian coast and Gulf of Mexico) by Kubar et al. [20] (see their Fig. 11(b)). Conversely, the behavior of oceanic clouds fell in between those of clouds in polluted coastal areas and the remote oceanic area reported by Kubar et al. [20] (also see their Fig. 11(b)) because the oceanic area in this study was relatively near the East Asian coast.
3.5 Fractional occurrences of precipitation categories using a two-dimensional plane

In this sub-section, the fractional occurrences of precipitation categories are further studied by the two-dimensional representations of $\tau_c$–$r_e$ and LWP–$N_c$ combinations, according to the method of Suzuki et al. [29]. As those authors stated, such an analysis provides a more detailed examination of warm rain formation than Figure 5 in terms of cloud properties in the two-dimensional representation, making the maximum use of the MODIS cloud retrievals.

Figure 6 shows fractional occurrences of precipitation categories as a function of $\tau_c$ and $r_e$ over land (a–c) and ocean (d–f). The overall behaviors of the contributions of $\tau_c$–$r_e$ to differences between non-precipitating and precipitation categories were similar between land and oceanic clouds. For example, the non-precipitating category generally occurs in the region of small $\tau_c$ with broad $r_e$ values and small $r_e$ with broad $\tau_c$ values, showing an L-like shape. The drizzle category mainly appears over the intermediate region between larger $\tau_c$ and smaller $r_e$ to smaller $\tau_c$ and larger $r_e$. The precipitating category occupies the remaining upper-right region having larger $\tau_c$ and $r_e$ values. Nevertheless, the precipitation category displays greater differences between land and oceanic clouds when compared to the other categories, such as greater frequencies of the precipitating category over larger values of $\tau_c$ and $r_e$ for oceanic clouds. It should be noted that the parameters of regional analyses such as ours, which do not cover the entire plane,
are inherently different from those of Suzuki et al. [29], who have conducted global ocean analyses.

Figure 7 shows fractional occurrences of the precipitation categories as a function of LWP and \( N_c \) over land (a–c) and ocean (d–f). The non-precipitating category was shown to occur generally over small LWP with broad \( N_c \) values. The drizzle category was found to take place over larger LWP and smaller \( N_c \) than the non-precipitating category. The precipitating category was shown to occur in the lower-right region of the \( N_c \)-LWP plane, corresponding to larger LWP and smaller \( N_c \). As in the \( \tau_c-r_e \) case, the precipitation characteristics in terms of the LWP–\( N_c \) plane are similar between land and oceanic clouds, although land clouds have smaller \( N_c \) values than oceanic clouds. For both the \( \tau_c-r_e \) and LWP–\( N_c \) cases, fractional frequencies of the precipitation categories are systematically shifted among non-precipitating, drizzle, and precipitating categories. As pointed out by Suzuki et al. [29], this approach can reveal how cloud properties contribute to each precipitation category, and how they tend to systematically vary among each precipitation category.

3.6 Vertical structure shown by a contoured frequency by optical depth diagram (CFODD)

By combining the specific attributes of CloudSat and MODIS data, detailed vertical features and structures of cloud microphysical process can be revealed as
previously reported by Nakajima et al. [14] and Suzuki et al. [15]. These studies offered a new diagram called the contoured frequency by optical depth diagram (CFODD) using optical depth as the vertical coordinate, instead of geometric height, to describe the vertical profile of the radar reflectivity, which is taken as the horizontal coordinate. Suzuki et al. [15] utilized the cloud adiabatic model to distribute in-cloud optical depth from the total optical depth determined from MODIS shortwave radiances, providing a vertical slicing of the optical depth in a manner independent of the radar reflectivity profile information. We adopted this CFODD approach to investigate the vertical structures of water clouds over land and ocean. We classified CFODDs according to $N_c$ to directly interpret the relationships of cloud parameters in the context of the aerosol indirect effect, following KS12. This approach differs from those of Nakajima et al. [14] and Suzuki et al. [15], who classified CFODDs according to $r_e$. To examine the transitional characteristics of cloud vertical profiles, three $N_c$ categories, referred to as $N_1$, $N_2$, and $N_3$, were introduced to correspond with higher, moderate, and lower cloud droplet number populations, respectively. Thresholds of 80 cm$^{-3}$ and 120 cm$^{-3}$ were used to divide these categories for both land and oceanic cloud analyses. The CFODDs for $N_1$, $N_2$, and $N_3$ are shown in Fig. 8(a–c) and (d–f) for measurements over land and ocean, respectively. Overall, the main features describing a transition from $N_1$ to $N_3$ were similar between oceanic and land clouds. More specifically, high-frequency regions shifted to a larger $Z_e$ and a smaller $\tau_c$ as $N_c$ decreased from $N_1$ to $N_3$. KS12 interpreted this phenomenon as follows: after the cloud development stage, $N_c$
decreases and \( r_e \) increases through coalescence, resulting in a decrease in \( \tau_c \) due to a
reduction in the total cross-section of particles. Moreover, the total water within clouds
decreases with precipitation events. Evaporation might also decrease the particle size and
eliminate particles, both of which result in \( \tau_c \) decreasing via liquid water loss. Figure 8(a)
and Fig. 8(d) for the \( N_1 \) case are generally similar and frequent at smaller \( Z_e \). Figure 8(b)
and Fig. 8(e) of the \( N_2 \) case are also similar, moving to slightly larger \( Z_e \) than the \( N_1 \) case.
As for the \( N_3 \) case, Fig. 8(f) shows that oceanic clouds are more frequent in optically
thicker and larger \( Z_e \) regions, which suggests more precipitation, compared to the land
clouds shown in Fig. 8(c). A larger \( Z_e \) corresponds to larger \( r_e \), which is consistent with
the larger \( r_e \) of oceanic clouds. Moreover, the \( N_3 \) cases are even more different from the
\( N_1 \) and \( N_2 \) cases, particularly for oceanic clouds.

4 Conclusions

Following KS12, who analyzed water cloud microphysical and transitional
processes over the Amazon and China using a combination of both active radar (CloudSat)
and passive radiometer (MODIS) data, we applied the same analysis approach to
mid-latitude water clouds to examine land–ocean differences in relationships among
cloud droplets, drizzle, and precipitation. The cloud parameters used were \( \tau_c \) and \( r_e \) from
MODIS; LWP and \( N_c \) as by-products of \( \tau_c \) and \( r_e \); and \( Z_e \) from CloudSat. We analyzed the
following parameters with the synergistic use of active CloudSat and passive MODIS
data: 1) PDFs of cloud parameters, 2) PDFs of cloud parameters as a function of $Z_e$, 3) fractional occurrences of precipitation categories as a function of the LWP, 4) fractional occurrences of precipitation categories as a function of $\tau_c$ and $r_e$, and of the LWP and $N_c$, and 5) vertical cloud structure using CFODD.

The PDFs of cloud optical and microphysical parameters were reasonable and consistent with previous studies, such that $r_e$ was smaller and $N_c$ was larger for land clouds. These results support Twomey’s idea regarding the differences in aerosol abundance between land and ocean. Although the distributions of $\tau_c$ were similar between land and oceanic clouds, LWP was larger for oceanic clouds owing to larger values of $r_e$.

For the PDF of $Z_e$, both land and oceanic clouds had bimodal shapes. We also found that the oceanic clouds had a larger mode of $Z_e$ and higher frequencies at the larger $Z_e$ range.

Then, we classified the precipitation characteristics into the four categories non-precipitating, drizzle, precipitating, and total-precipitating, using the thresholds of $-15$ and $0$ dBZ to divide categories. Next, we analyzed the PDFs of cloud parameters as a function of $Z_e$ in order to examine how they tend to change with changing $Z_e$, taking $Z_e$ as the horizontal coordinate and the PDFs of cloud parameters as the vertical coordinate.

Figures 3 (a)–(d) and 4 (a)–(d) illustrate the results over land and ocean for $\tau_c$, $r_e$, LWP, and $N_c$, respectively. Although monotonic trends were observed for both land and oceanic cloud parameters, such as positive trends of $\tau_c$, $r_e$, and LWP and a negative trend of $N_c$, on the whole, land cloud parameters showed less distinct trends for $Z_e > 0$ dBZ. Then, the fractional occurrences of these precipitation categories were examined as a function of
the LWP (Fig. 5). General trends were found to be very similar between land and oceanic clouds, such as a monotonically decreasing trend in the non-precipitating, a convex shape for the drizzle, and monotonically increasing trends of both the precipitating and total-precipitating categories. Although both land and oceanic clouds showed the convex shape for the drizzle category, the peak value of LWP was larger for land clouds, implying that more cloud water is required for drizzle particles to form over land than over ocean because of smaller cloud droplets over land. The same tendencies were also found in the precipitating category that shows larger LWP values over land for the fractional occurrence to reach the same value as over ocean.

We further analyzed the fractional occurrences of the precipitation categories in terms of two-dimensional representations of cloud parameters, such as combinations of $\tau_c-r_e$ and LWP–$N_c$, instead of the LWP alone. Systematic changes in the transition regarding pairs of the cloud parameters were captured well for all precipitation categories. The transition pattern was generally similar between land and oceanic clouds. As Suzuki et al. [29] suggested, use of this two-dimensional method can reveal the detailed characteristics of cloud parameters and fractional occurrences of each precipitation category. Finally, the CFODD diagram, with $\tau_c$ as the vertical coordinate and $Z_e$ as the horizontal coordinate, was used to classify cloud development stages in terms of $N_c$. This CFODD approach may also reveal the transitional characteristics of cloud vertical structure. In particular, oceanic clouds were found to produce heavier precipitation from optically thicker regions than land clouds in $N_3$. This is consistent with Fig. 2(e), which
shows that the oceanic clouds had larger modes of $Z_e$ and were more frequent in the larger $Z_e$ range. However, whether a cloud was of land or oceanic origin made little difference in $N_f$.

At last, let us summarize the discussion on relations among $\tau_c$, $r_e$, LWP and $N_c$.

The LWP and $N_c$, which were derived from and were not independent of $\tau_c$ and $r_e$ in this study, are important parameters in current analyses such that the LWP is taken as the $x$-axis in fractional occurrences of the precipitation category of Fig. 5, and $N_c$ is used as the threshold in the CFODD of Fig. 8. From the viewpoint of cloud physics, the behaviors of $\tau_c$, $r_e$, LWP, and $N_c$ so obtained can be summarized as follows. Using the PDFs as a function of the $Z_e$ in Figs. 3 and 4, $\tau_c$, $r_e$, and the LWP monotonically increase with $Z_e$, storing water mass inside the cloud layer, while $N_c$ is decreased due to the collision–coalescence process, which produces raindrops and whose temporal progress can be seen from the left to the right in Figures 3 and 4.

Future work regarding this study can be mentioned as follows. It would be useful to extend these kinds of analyses to various locations across the globe, in addition to the mid-latitudes examined in this study, and to determine differences and similarities in microphysical features. Recently, Zhu et al. [30] proposed a mechanism for the aerosol concentration increase due to weakening of the East Asian summer monsoon. It would be quite interesting in this context to examine the correlation between the aerosol concentration and precipitating/non-precipitating frequencies over various locations, as well as over East Asia. Furthermore, Lebsock et al. [3] derived vertical profiles of
precipitation rate and discussed the ratios of rain and cloud water for oceanic low-level clouds. A vertical analysis of precipitation rate, when combined with the current approach, may help to clarify the transitional processes involved in cloud droplet, drizzle, and precipitation formation inside the cloud layer.

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References


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Figure 1. Map of the regions analyzed in this study. The solid and dotted circles represent the land areas (within 1000 km from 35°N and 105°W over China) and oceanic areas (within 1000 km of 35°N and 165°E over the northwest Pacific) included, respectively.

Figure 2. Probability distribution functions of (a) $\tau_c$, (b) $r_e$, (c) LWP, (d) $N_c$, and (e) $Z_e$ for land and oceanic clouds. The two threshold values of -15 and 0 (dBZ) were imposed in Fig. 2(e).

Figure 3. Probability distribution functions of (a) $\tau_c$, (b) $r_e$, (c) LWP and (d) $N_c$ as a function of $Z_e$ for land clouds.

Figure 4. As in Fig.3, but for oceanic clouds.

Figure 5. Fractional occurrences of (a) non-precipitating, (b) drizzle, (c) precipitation, and (d) total-precipitation as a function of the LWP for land and oceanic clouds.

Figure 6. Fractional occurrences of (a) non-precipitating, (b) drizzle, and (c) precipitation as a function of $\tau_c$ and $r_e$ for land and oceanic clouds.

Figure 7. As in Fig.6, but as a function of LWP and $N_c$. 
Figure 8. CFODDs of the (a) land clouds for $N_1$, (b) land clouds for $N_2$, (c) land clouds for $N_3$, (d) oceanic clouds for $N_1$, (e) oceanic clouds for $N_2$ and, (f) oceanic clouds for $N_3$. 
Fig. 2 (a)
Fig. 2 (b)
Fig. 2 (c)
Fig. 2 (d)

Frequency

Cloud droplet number density \( (1/cm^3) \)
Fig. 2 (e)
Fig. 3

(a) Cloud optical depth

(b) Effective Particle Radius

(c) Liquid Water Path

(d) Droplet number density

Legend: 0 - 20 (dBZ)
Fig. 5 (a)
Fig. 5 (b)
Fig. 5 (c)
Fig. 5 (d)
Effective Particle Radius (µm) vs. Cloud Optical Depth

- (a) non-precipitating
- (b) drizzle
- (c) precipitating

Fig. 6 (a) (b) (c)
Droplet number density (cm$^{-3}$) non-precipitating, drizzle, precipitating

Liquid water path (g/m$^2$)

Fig. 7 (a) (b) (c) (d) (e) (f)