Tibetan Plateau Cloud Structure and Cloud Water Content Derived from Millimeter Cloud Radar Observations in Summer

YUJUN QIU,¹ CHUNSONG LU,¹ and SHI LUO¹

Abstract—The properties of cloud occurrence frequency and cloud water content (CWC) in warm cloud layers (WCLs), mixed-phase cloud layers (MCLs) and ice cloud layers (ICLs) over the Naqu site of the Tibetan Plateau were characterized by using ground-based millimeter cloud radar (MMCR) data and aircraft observations from July 6–31 in 2014. Statistically, the total probabilities of clouds during the 0:00–6:00 (T1), 6:00–12:00 (T2), 12:00–18:00 (T3) and 18:00–24:00 (T4) local standard time (LST) periods were approximately 82.7, 56.2, 55.3 and 65.4%, respectively. The maximum heights of cloud layers under cloudy, drizzle/weak precipitation and precipitation conditions have large differences during T1, T2, T3 and T4 periods. The average values of the retrieved liquid water content (LWC) in the WCLs was approximately 75.2 mg/m³, ranging from high to low during the 4 periods of T3, T2, T4 and T1. The CWC in the MCLs decreased with an increase in height from 86.8 to 9.5 mg/m³, and the mean value was 33.1 mg/m³. The ice water content (IWC) decreased with an increase in height from approximately 9.5 mg/m³ at 5.0 km to 4.8 mg/m³ at 11 km. These results provided unprecedented details concerning the cloud structure and especially about CWC in different phases over the Tibetan Plateau and may be used to improve the parameterization of clouds in various models.

Key words: Mixed-phase clouds, liquid water content, ice water content, MMCR, Tibetan Plateau.

1. Introduction

The Tibetan Plateau (TP) exerts profound thermal and dynamic influences on atmospheric circulation due to its complex terrain and unique atmospheric conditions, with an average elevation of 4.5 km

above sea level (Yanai et al. 1992; Wu et al. 2007); therefore, it hosts a variety of cloud features and exerts significant effects on the global and regional climate systems (Yang et al. 2014). Although tremendous efforts have been made to obtain information on cloud macrophysics (e.g., cloud cover) and cloud microphysics (e.g., water content) over the TP (For example, Fujinami and Yasunari 2001; Chen and Liu 2005; Li et al. 2006; Taniguchi and Koike 2008; He et al. 2013; You et al. 2014; Zhao et al. 2014, 2016, 2017; Liu et al. 2015), more knowledge of cloud properties based on high-spatiotemporal-resolution observations is always needed to accurately understand the thermal and dynamic effects of the TP on the atmosphere.

Recently, based on high-resolution remote sensing data such as the W-band Cloud Profiling Radar (CPR) and lidar, many studies concerning TP clouds have been published (He et al. 2013; Zhao et al. 2014, 2016, 2017; Liu et al. 2015; Chang and Guo 2016; Song et al. 2017). He et al. (2013) analyzed the cirrus cloud geometry and optical characteristics in summer over the TP using micropulsed lidar, and found that there were obvious differences between the TP and other areas at the same latitude. Zhao et al. (2014) analyzed the distribution of the TP total water path (TWP) in clouds and its seasonal variations by using CloudSat data, and found that the value of the TWP during the warm season was greater than that during the cool season, and the vertical distribution of precipitation clouds over the TP was quite different from that over East Asia. Specifically, based on the intensive observations of clouds and precipitation in the third TP experiment of atmospheric sciences (TIPEX III), many studies have provided the properties of clouds over the TP. Liu et al. (2015)

¹ Key Laboratory of Meteorological Disaster, Ministry of Education (KLME)/Joint International Research Laboratory of Climate and Environment Change (ILCEC)/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD)/Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science and Technology, Nanjing 210044, China. E-mail: qyj@nuist.edu.cn

carried out research on the microphysical and macroscopic features of clouds and precipitation using multiple-wavelength radar and lidar devices during TIPEX III and found that the statistical parameters of clouds had obvious diurnal variations. Chang and Guo (2016) analyzed the characteristics of convective clouds and the distribution of precipitation and showed detailed daily variations. Zhao et al. (2016) and Zhao et al. (2017) described the microphysical properties of high ice clouds and the microphysical properties of low-level liquid clouds, which provided an effective radius for ice and liquid clouds as well as ice water and liquid water contents. Song et al. (2017) showed cloud occurrence frequencies, cloud base and top heights and diurnal variations by using ceilometer, water vapor and lidar data.

The results from the above studies provide the diurnal variations and properties of cloud occurrence frequencies, cloud bases and heights, cloud effective radii and cloud water content (CWC). However, the microphysical properties of clouds in different phases, especially in mixed cloud layers with both liquid and ice phases, still need to be improved, and synthesized information on entire cloud layers also needs to be provided. In this paper, we use the data from outfield experiments over the TP which provide new data for analyzing physical processes of clouds and precipitation over the TP. The vertical structure of cloud macrophysics and microphysics can be provided through the detection using the Ka band millimeter wave cloud radar with high spatial and temporal resolution. We studied cloud structure and water content by dividing cloud layers into different phase layers based on temperature. The results about cloud structure and especially about CWC in different phases over the TP may provide insight into the characteristic properties of clouds and may be used to improve the parameterization of clouds in various models in summer over the TP.

2. Data and Methods

2.1. Data

Continuous ground-based 35-GHz millimeter cloud radar (MMCR) measurements were carried

out in the third TP experiment of atmospheric science (TIPEX III) at the Naqu Meteorological Bureau site (31.48°N, 92.06°E; 4508 m above mean sea level) from 1 July to 31 July 2014. The MMCR can provide resolved information on cloud structures at vertical and temporal resolutions of 30 m and 8.8 s, respectively, by operating in the Ka band with a peak transmitter power of 50 W. The MMCR works in a vertical manner, with a measurement range from 120 m to 15 km. The measurements include radar reflectivity, Doppler velocity, radar spectrum width, depolarization ratio, and power spectra. The effective values of reflectivity range from -50 to 30 dBZ which is suitable for nonprecipitating or weakly precipitating clouds.

There are three modes of the MMCR observations, which are the boundary mode (BM), cirrus mode (CM), and rain mode (RM). Zhao et al. (2016) and Zhao et al. (2017) retrieved the liquid water content (LWC) of low-level liquid clouds using the BM and the ice water content (IWC) of high ice clouds using the CM. Here, we retrieved the LWCs of liquid clouds and mixed-phase clouds and the IWCs of mixed-phase clouds and ice clouds by using the BM and CM, respectively.

In addition, aircraft observations were conducted as part of the TIPEX III project (see Fig. 1). The aircraft data were used to verify the retrieval of LWCs in clouds by using the MMCR data. The data were selected in the region 31–33°N, 91–93°E (see Fig. 1a). The aircraft flew several runs at different altitudes from 1.8 to 4.5 km and measured the LWC and temperature (see Fig. 1b, c). A summary of the aircraft maneuvers during the flight is provided in Table 1. The LWC data are derived from measurements using the Nevzorov probe.

2.2. Methodology

First, we classified the cloud layers as warm cloud layers (WCLs), mixed-phase cloud layers (MCLs) and ice cloud layers (ICLs), which are characterized by phases of pure liquid, liquid and ice (i.e., mixed) and pure ice, respectively. The cloud phase was related to the status of the atmospheric temperature. Based on the radiosonde and MMCR observations at a specified height, Zhao et al. (2016) and Zhao et al.

Figure 1

Aircraft observation information from six flights over the Naqu Meteorological Bureau site during the third Tibetan Plateau experiment of atmospheric science (TIPEX III): **a** flight tracks, **b** vertical distributions of liquid water content (LWC), and **c** temperature profiles

Table 1

Summary of aircraft observations over the Naqu site during July 2014

Date	Flight time (LST)	Weather conditions	Flight height (km)	Averaged LWC (mg/m^3)	Maximum LWC (mg/m^3)	Standard deviation LWC (mg/m^3)
20140703	10:48–11:48	Sunny, light cumulus	1.2–4.1	10.2	105.6	10.8
20140710	10:40–11:53	Cloudy, cumulus	1.8–4.1	16.8	211.5	30.9
20140720	10:40–11:47	Cloudy, cumulus	1.8–4.4	22.8	261.1	40.9
20140721	10:30–11:30	Cloudy, cumulus	1.8–4.4	30.7	295.5	40.1
20140724	11:30–13:55	Cloudy, cumulus	1.7–4.4	24.6	149.6	23.8

(2017) assumed that clouds above 5 km were composed of in-phase pure ice and those below 1.2 km were composed of in-phase water, which was consistent with the aircraft observations presented in Fig. 1c [see the reference from Zhao et al. (2018)] and the findings by Liu et al. (1999). We assumed the cloud layers below 1.2 km to be WCLs, the MCLs to be between 1.2 and 5 km, and the ICLs to be above 5 km based on the results of Zhao et al. (2016) and Zhao et al. (2017). Note that the height in this paper refers to the altitude above ground level.

Second, by considering the effects of different reflectivity values on the average reflectivity value, the whole MMCR reflectivity range (from -50 dBZ to 30 dBZ) was divided into 16 equal sub-ranges (i.e., the first range was from -50 to -45 dBZ, and the sixteenth range was from 25 to 30 dBZ). The probabilities of different reflectivity ranges were determined in four 6-h periods during 1 day from

0:00 to 6:00 local standard time (LST; i.e., the T1 period), 6:00–12:00 (T2), 12:00–18:00 (T3) and 18:00–24:00 (T4). Note that the MMCR observations were operated in the boundary mode to detect low-level boundary layer clouds and fog events with weak reflectivity and small Doppler velocity below 2.04 km; these observations were also operated in cirrus mode, which is sensitive at heights between 2.04 and 15.3 km. By considering the continuity of a cloud in terms of vertical height, the probabilities of reflectivity in boundary mode and cirrus mode at a 2.04-km height were set as equal values and smoothed below 2.04 km. Thus, the mean reflectivity profiles in the different periods during 1 day were calculated based on the probability distribution functions (PDFs) of the clouds.

Finally, the LWC of clouds was retrieved based on the forward model algorithm and by assuming a log-normal size distribution (Austin et al. 2009). The

number density of the cloud droplets was assumed to obey a logarithmic normal distribution function, as shown in Eq. (1).

$$N(R) = \frac{N_T}{\sqrt{2\pi R \ln W_g}} \exp \left[\frac{-\ln^2(R/R_g)}{2 \ln^2 W_g} \right] \quad (1)$$

where R represents the particle size of the cloud droplet, $N(R)$ represents the number density for a particle size of R , N_T represents the total number density, W_g represents the standard deviation, and R_g represents the geometric average radius. Equation (1) can be used to derive the relationships among the LWC, radar albedo factor (Z), N_T , R_g , and W_g , as shown in Eqs. (2)–(3).

$$\text{LWC} = \frac{4\pi}{3} N_T \rho_w R_g^3 \exp \left(\frac{9}{2} W_g^2 \right) \quad (2)$$

$$Z = 64 N_T R_g^6 \exp(18 W_g^2) \quad (3)$$

where ρ_w represents the cloud droplet density. During the retrieval process, we need to set a vector of the prior values for N_T , R_g , and W_g , which form a prior value vector (x_a) and a covariant matrix of prior values, S_a . The optimal retrieval solution is determined by the iterative convergence of Eq. (4).

$$\chi^2 = [y - F(x)]^T S_y^{-1} [y - F(x)] + (x_a - x)^T S_a^{-1} (x_a - x) \quad (4)$$

$$F(x) = \begin{bmatrix} Z'_{\text{dB}_{\text{FM}}}(z_1) \\ \vdots \\ Z'_{\text{dB}_{\text{FM}}}(z_p) \end{bmatrix} \quad (5)$$

In Eq. (4), y represents the measured value of different height levels for Z , and $F(x)$ represents the first-order derivative of various cloud layers for Z , which can be derived by taking the derivative of Eq. (3). In Eq. (5), z_1 and z_p represents the heights of the cloud top and cloud base, respectively. Details of the retrieval algorithm used here can be found in Austin et al. (2009), Qiu et al. (2015), and Qiu and Lu (2016).

In addition, when retrieving the LWC in the MCLs, only liquid water was first assumed in cloud layers and retrieved, then the LWC was multiplied by the liquid water-to-ice water mixing ratio to derive

the final LWC. The liquid water-to-ice water mixing ratio p_1 in the MCLs was calculated according to Eq. (6), as per Austin et al. 2009, which has been used to produce the CloudSat 2B product.

$$p_1 = \frac{T - T_{\min}}{T_{\max} - T_{\min}} \quad (6)$$

In Eq. (6), T , $T_{\min}$, and $T_{\max}$ represent the average, minimum, and maximum value of temperature in cloud layers, respectively.

Qiu et al. (2015) suggested the liquid water-to-ice water mixing ratio p_2 based on Eq. (7) was more appropriate than p_1 in Eq. (6) in the MCL. Here, Eq. (7) was used.

$$p_2 = \frac{\exp(3p_1) - 1}{\exp(3) - 1} \quad (7)$$

To obtain the column-averaged CWC of the whole cloud layers, the IWCs were retrieved based on an empirical function provided by Zhao et al. (2016) who used the same MMCR data, based on Eq. (8).

$$\text{IWC} = 0.097 Z_e^{0.59} \quad (8)$$

where Z_e is the radar reflectivity.

3. Results and Discussion

3.1. Cloud Layer Properties

3.1.1 Probability Distribution

The cloud probability distributions (CPDs) were presented based on the radar reflectivity statistics in July of 2014 (see Fig. 2).

Statistically, the PDFs for the whole cloud layer during the four periods showed two peak areas. The probabilities of whole cloud layer during T2, T3, and T4 are distributed in the two peak areas while the probabilities are mainly concentrated in the first peak area during T1. The first peak area occurred in reflectivity ranges below -15 dBZ and the second peak area occurred above -15 dBZ. A reflectivity value of -15 dBZ found via the 35-GHz cloud radar was suggested as a reference value for drizzle and weak precipitation occurrences (Fox and Illingworth 1997; Matrosov et al. 2004; Suzuki et al. 2010).

Figure 2

Cloud probability distribution functions for reflectivity ranging from -50 to 30 dBZ observed by the MMCR over the Naqu site during four time periods throughout the **a** whole layer, **b** warm cloud layers, **c** mixed-phase cloud layers, and **d** ice cloud layers. The dark-blue lines with triangles, red dotted lines, black lines with triangles, and light-blue dotted lines represent the time periods of 0:00–6:00, 6:00–12:00, 12:00–18:00, and 18:00–24:00 LST, respectively

Reflectivity in ranges of less than -15 , from -15 to 0 , and 0 to 15 dBZ were interpreted as corresponding to cloud, drizzle/weak precipitation, and precipitation, respectively (Suzuki et al. 2010). This implied that the total probabilities of clouds in T1, T2, T3, and T4 were 82.7, 56.2, 55.3, and 65.4%, respectively; these are 6.5, 1.7, 1.6, and 2.4 times greater than the drizzle/weak precipitation probabilities, and 17.7, 4.9, 5.9, and 8.4 times greater than the precipitation probabilities, respectively. From the contrast between cloud and precipitation probabilities in T1, T2, T3, and T4, it shows the clouds that occurred from 0:00 to 6:00 were more significant than those that occurred under drizzle and precipitation

conditions, which appeared most frequently from 12:00 to 18:00. This was related to the diurnal variations in water vapor. Intense sensible heating over the TP in summer provides thermodynamic conditions for the development of convective activities on the plateau. The boundary layer reaches the highest temperature in the afternoon and higher temperature in the evening, which leads to the instability of the stratification over the plateau and the increase of the large-scale updraft, which is beneficial to the convective activity and the occurrence of precipitation. Sato et al. (2008) studied clouds over the TP with a mesoscale model and showed that the black body temperature of clouds

reached large values from 13:00 to 20:00 during the daytime. Fu et al. (2006) found that summer rainfall reached its maximum value at approximately 16:00 and a minimum at approximately 5:00. In addition, the lower atmosphere is mainly dominated by convergence airflow over the TP from noon to the evening in summer. The rising movement and relative humidity are stronger than those from night to dawn, which is beneficial to the occurrence of precipitation. The divergence mainly appears during the evening and the early morning and the clouds do not develop easily into precipitation (Chang and Guo 2016), which is in accordance with the statistical results in Fig. 2. As shown in Fig. 2-a, the highest probability under the cloud condition in the first peak area appears in T1, and the highest probability under the drizzle and precipitation condition appears in T3. Based on the TIPEX III data, Chang and Guo (2016) found that there is a significant diurnal variation on the process of convective clouds and precipitation. Convective activities are developed by local geothermal convection at 11:00 (LST) and reaches their strongest activity from 17:00–18:00; convection, then weakens to dissipate at night and there is less convective activity in the morning.

The probabilities of cloud, drizzle/weak precipitation, and precipitation in different phase cloud layers showed significant differences, as shown in Fig. 2b–d. In the WCLs, cloud probability that occurred in the first peak area during T1, T2, T3 and T4 were 83.7, 58.6, 50.2 and 66.5%, which were 5.1, 1.4, 1.0 and 2.0 times greater than those that occurred in the second peak area, respectively. This means that drizzle and precipitation occurred most frequently from 12:00 to 18:00 during the daytime which is consistent with the findings in the literature (For example, Fu et al. 2006; Sato et al. 2008; Bai et al. 2008; Chang and Guo 2016), and the frequencies of these conditions were comparable to the cloud frequencies.

In the MCLs, clouds that occurred in the first peak area were 79.0, 49.8, 41.6 and 57.6% during T1, T2, T3 and T4, respectively. This implied that the drizzle and precipitation conditions during the daytime were consistent with the occurrence of clouds, and the frequency of clouds at nighttime was greater than the frequencies of drizzle and precipitation of

approximately 3.8 and 1.4 times from 0:00 to 6:00 and 18:00 to 24:00, respectively. That is, drizzle and precipitation mainly occurred during the daytime, which is consistent with the results of Sato (Sato et al. 2008).

In the ICLs, the cloud frequency showed a unimodal distribution that was focused over cloudy areas, with proportions of 87.6, 62.1, 67.5 and 74.1% during T1, T2, T3 and T4, which were 7.2, 1.9, 2.3 and 3.0 times greater than those of drizzle and precipitation, respectively. This means that less drizzle and precipitation occurred in the ICLs than in the WCLs and MCLs.

3.1.2 The Heights of Cloud Layers

Figure 3 shows the vertical profiles of cloud probability for four 6-hour periods during a day in eight sub-ranges of reflectivity. The maximum heights (MHs) of the cloud layers (Fig. 3) during the four periods appeared to have large differences, which were affected by surface thermodynamic conditions. The MHs under cloudy condition during T1, T2, T3 and T4 were approximately 10.9, 12.5, 12.4 and 12.4 km, respectively. The MHs under drizzle conditions were approximately 8.5, 12.1, 11.9 and 11.5 km during T1, T2, T3 and T4, respectively. This implies that the MHs under cloudy and drizzle conditions from 0:00 to 6:00 were lower than those during other periods, which may be due to the fact that the stable boundary layer in T1 was affected by the thermal dynamic diurnal cycle (Yanai and Li, 1994).

Moreover, the MHs under precipitation conditions showed large differences during the daytime and nighttime periods. The ranges from 0 to 10 dBZ, 10 to 20 dBZ and above 20 dBZ corresponded to precipitation conditions with a low reflectivity value range (LRVR), medium reflectivity value range (MRVR) and high reflectivity value range (HRVR), respectively. The MHs under precipitation conditions in the LRVR reached 10.9 and 11.0 km during T2 and T3, and 6.5 and 7.4 km during T1 and T4, respectively. The MH in the MRVR reached a 6.9- and 9.8-km height during T2 and T3, 4.0 km during T1 and 4.6 km during T4 at low levels at nighttime. The probability of a HRVR mainly appeared during

Figure 3

The vertical profiles of cloud probability based on the conditions of reflectivity ranging from -50 to 30 dBZ observed by the MMCR over the Naqu site during four time periods. **a–d** represent the periods of 0:00–6:00, 6:00–12:00, 12:00–18:00 and 18:00–24:00 during 1 day, respectively. The blue and red horizontal dotted lines represent the average altitude of -20 and 0 °C, respectively

T2 and T3, with MHs approximately 4.0 km and 4.7 km, respectively. The MHs during the daytime periods, especially during T3, were higher than those during the nighttime periods, which was related to the thermal dynamic features. That is, the diurnal variations in the thermal dynamics over the TP were significant, as convection in the boundary layer began to develop at 9:00 LST, increase sharply at 12:00 and reach a maximum at 15:00 (Fujinami and Yasunari 2001; Yang et al. 2004).

As shown in Fig. 4a, there are two layers where the probability under cloudy and drizzle conditions increased greatly with increasing height. One was the layer below 3.5 km, and the other was the layer from 6 to 9 km. Less clouds appear above 9 km which is

affected by humidity inversion (Chang and Guo 2016). The humidity inversion makes less clouds and then inhibits the development of convection over the TP. The probability under precipitation conditions increased greatly only in the layers below 3.5 km (see Fig. 4b). The cumulative probabilities at the 3.5-km layer during T1, T2, T3 and T4 reached 56.5, 44.5, 36.9 and 46.3%, respectively. It is shown that clouds below 3.5 km occurred more frequently at night than during the day. Moreover, the cumulative probability of the whole reflectivity range increased minimally in the 4–5-km layer. This indicates that clouds occurred less in the 4 to 5-km layer, which is consistent with the findings of Liu et al. (2015). The cumulative probabilities at a 9-km height during T1, T2, T3 and

Figure 4

Cloud cumulative probability profiles for reflectivity ranges **a** below 0 dBZ and **b** above 0 dBZ. The dark-blue, light-blue, red and black lines represent the periods of 0:00–6:00, 6:00–12:00, 12:00–18:00 and 18:00–24:00 LST during 1 day, respectively. The black, blue and red horizontal lines represent the heights of 11 km and the average altitude of -20 and 0 °C, respectively

T4 reached 97.4, 90.8, 90.4 and 96.0%, respectively. This indicated that ice clouds occurred at a less than a 10% rate above the 9-km layer. Considering that probability above 11 km was less than 0.5% for the 4 periods, we focused our research on the layers below 11 km in the following analysis.

3.1.3 The Reflectivity Profiles

To give an expression for information concerning the average cloud reflectivity, mean reflectivity profiles were calculated based on frequency spectrum profiles for 16 sub-reflectivity categories (see Fig. 5). The calculated reflectivity based on the frequency spectrum can reflect the comprehensive cloud level, which eliminates the influence of high values of reflectivity on the total mean value. Figure 5a provides the average values of the calculated reflectivity by considering cloudy, drizzle, and precipitation probabilities together, and Fig. 5b shows the calculated reflectivities by only considering the cloudy and drizzle probabilities. The reflectivity profiles had a similar trend with height during the four periods, but the values of reflectivity showed large differences in Figs. 5a, b, which appeared significantly in the WCLs that were related to the large values of reflectivity under precipitation

conditions (see Fig. 5c). Statistically, the reflectivity profiles that only considered nonprecipitation clouds in Fig. 5b were more reasonable than those in Fig. 5a.

In general, the values of the reflectivity profiles during the daytime periods were larger than those during the nighttime periods in the WCLs and the MCLs and exhibited an increasing trend with an increase in height. The values of reflectivity during T1 were the smallest, and the values during T3 were the largest of the four periods when orographic or convective clouds existed (Chen et al. 2012; Wang et al. 2015). The reflectivity profiles in the ICL showed a decreasing trend with increases in height.

3.2. LWCs and IWCs

The LWCs and IWCs provided in Fig. 6 only include cloudy and drizzle conditions without considering precipitation condition. As shown in Fig. 6a, the LWCs in the WCLs increased with height from approximately 80.1 mg/m^3 at 0.12 km to 85.5 mg/m^3 at 1.2 km, which is consistent with the findings of Li and Ligeer (2001), who studied in situ aircraft observations over the northeastern TP. Zhao et al. (2012) and Zhao et al. (2017) also presented similar results. The reason is that as air masses expand, lose energy and become cold, moisture condenses into liquid water, which makes both the cloud droplet size and LWC increase as the air mass moves upward. Sharp changes in the linear slopes of the LWC at the upper levels in the WCLs may be caused by relatively stronger air exchanges between the internal and external regions of upper-level clouds. The LWCs were ordered from high to low as follows: T3, T2, T4 and T1.

The LWC (IWC) in the MCLs decreased (increased) with increasing height, which followed a roughly exponential function, and was related to the corresponding temperatures used in the retrieval process. Specifically, the LWC appeared to have a sharp decrease at 1.2 km because the LWC in the MCLs was multiplied by the liquid water-to-ice water mixing ratio to derive the final LWC, and the liquid water-to-ice water mixing ratio decreased with height according to the exponential function for

Figure 5

Average profiles of cloud reflectivity during the 4 periods, which were calculated based on the frequency spectra of clouds in reflectivity ranges **a** from -50 to 30 dBZ and **b** from -50 to 0 dBZ where **c** shows the difference between **a** and **b**. The dark-blue, light-blue, red, and black triangle lines represent the periods of 0:00–6:00, 6:00–12:00, 12:00–18:00, and 18:00–24:00 LST during 1 day respectively. The blue and red horizontal lines represent the average altitude of -20 and 0 °C, respectively

temperature. The order of the average LWC values in the MCLs from high to low was T3, T2, T4 and T1.

Zhao et al. (2016) retrieved the IWC by using the same MMCR observation data, and we quoted their IWC retrieval method here. The IWCs in the ice layers decreased weakly with increasing height, going from approximately 9.5 mg/m^3 at 5.0 km to 4.8 mg/m^3 at 11 km . The values of the IWC in every ice layer during T1 were the smallest of the four periods.

We then analyzed the diurnal variations in monthly average LWC and IWC in different phase layers in more detail. Figure 6 shows the overall diurnal variations in LWC, IWC and CWC in July 2014 over the TP. The monthly mean LWC in the WCLs was approximately 75.2 mg/m^3 , which is comparable to that of Zhao's (Zhao et al. 2017). A relatively weak maximum LWC occurred in the early morning (see Fig. 7a). On the other hand, by considering the LWCs in the WCLs and MCLs

together, the diurnal characteristic properties of LWCs showed a significant maximum value at approximately 14:00–16:00 (see Fig. 7d). The diurnal variations in the LWC were influenced by the diurnal solar radiation cycle and thermodynamics (Chang and Guo 2016). The diurnal variation in the LWC, with a maximum peak occurring during the afternoon and a minimum value that appeared during the period before sunrise, confirmed the control of surface thermodynamics on cloud formation over the TP. Li et al. (2008) pointed out that the total precipitation has a dominant peak at approximately 18:00 LST and a secondary maximum at approximately 3:00 LST.

The average LWC and IWC values in the MCLs showed clear diurnal characteristic properties. The LWCs and IWCs reached maximum values at approximately 14:00–16:00 and minimum values at approximately 4:00–6:00 (Fig. 7d, e, respectively). The average LWC was approximately 26.6 mg/m^3 , which was similar to the average values of the aircraft

Figure 6

a Average profiles of retrieved LWCs and IWCs of cloud layers during the periods of 0:00–6:00, 6:00–12:00, 12:00–18:00 and 18:00–24:00 LST; **b** Daily average value profile of retrieved CWC calculated based on **a**. The blue and red horizontal dotted lines represent the average altitude of -20 and 0 °C, respectively. The profiles in **a** and **b** above the altitude of -20 °C represent IWC profiles, the profiles between the altitude of -20 and 0 °C represent LWC and IWC profiles, and the profiles below the altitude of 0 °C represent LWC profiles

observations (see Table 1). In addition, the average IWC was approximately 6.5 mg/m^3 .

Above all, the diurnal variations in the CWC below 11 km appeared to have clear diurnal characteristic properties, with a maximum value of 26.1 mg/m^3 at approximately 14:00–16:00 and a minimum value of 17.6 mg/m^3 at approximately 4:00–6:00. We should note that the CWCs (or LWCs and IWCs) in Fig. 7 were averaged within the corresponding layers; the cloud water path (CWP) can be obtained by multiplying the CWC by the thickness of the corresponding layer. From Fig. 7c, we can obtain the monthly average CWP below 11 km, which was approximately 0.3 kg/m^2 .

4. Conclusions

In this paper, we analyzed and presented ground-based MMCR data to examine cloud characteristics. First, cloud occurrence frequencies in the warm layers, mixed-phase layers and ice layers were examined. Second, the CWCs, including their LWC and IWC, were retrieved. The diurnal and vertical

distributions of cloud properties in different cloud phase layers were dissected, which may provide insight into the characteristic properties of clouds over the TP and may be used to improve the parameterization of clouds in various models. The major conclusions are as follows:

1. The frequency of cloud occurrences at 0:00–6:00, 6:00–12:00, 12:00–18:00 and 18:00–24:00 LST were approximately 4.8, 1.3, 1.2 and 1.9 times greater than the frequencies of drizzle and precipitation, respectively. Compared with cloudy conditions, drizzle and precipitation conditions appeared frequently in the WCLs and MCLs at 12:00–18:00 and less frequently at 0:00–6:00 throughout the whole cloud layer.
2. Clouds attained a maximum height of approximately 12.5 km during the daytime period. Drizzle/weak precipitation can reach a maximum height of approximately 12.1 km from 6:00 to 12:00, but can reach only 8.5 km from 0:00 to 6:00. Precipitation with low reflectivity reached a maximum height of 7.4 km at night and 11.0 km during the daytime, and precipitation with large reflectivity reached a MH of 4.7 km mainly during the daytime.
3. The cumulative probability below 3.5 km and between 6 and 9 km increased greatly with increases in height. The probability below 3.5 km was approximately 46.1%. The cumulative probabilities were approximately 93.7% at 9 km and 99.6% at 11 km.
4. The reflectivity profiles calculated based on the frequency spectrum profiles showed an increasing trend in the WCLs and MCLs and a decreasing trend in the ICLs with an increase in height. The values of reflectivity from 0:00 to 6:00 were the smallest during the four 6-h periods for every cloud layer.
5. The mean LWC was approximately 75.2 mg/m^3 in the WCLs and 26.6 mg/m^3 in the MCLs. The mean IWC above the WCLs was approximately 6.4 mg/m^3 . Above all, the mean CWC reached a maximum value of 26.1 mg/m^3 at approximately 14:00–16:00 and a minimum value of 17.6 mg/m^3 at approximately 4:00–6:00.

Figure 7

Average values of CWC, LWC and IWC in cloud layers during daily hours. **a** Average values of LWCs in the warm cloud layers; **b** average values of LWCs in the mixed cloud layers; **c** average values of LWCs in the warm and mixed cloud layers; **d** average values of IWCs; **e** average values of CWCs in the layers below 11 km and **f** average values of CWCs in the mixed cloud layers. The vertical lines in **a–c**, **e** and **f** represent the ranges of average values from the maximum to the minimum

Acknowledgements

We would like to acknowledge the support of the Third Tibetan Plateau Experiment of Atmospheric Science (TIPEX III) for providing the data. This study was funded by the National Key Research and Development Program on Monitoring, Early Warning and Prevention of Major Natural Disaster (2017YFC1502103), the National Natural Science Foundation of China (grant no. 41475035, 91537108); and China Meteorological Administration Special Public Welfare Research Fund (grant no. GYHY201406001); and the Natural Science Foundation of Jiangsu Province of China (grant no. BK20160041).

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted

use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

REFERENCES

- Austin, R. T., Heymsfield, A. J., & Stephens, G. L. (2009). Retrieval of ice cloud microphysical parameters using the CloudSat millimeter-wave radar and temperature. *Journal of Geophysical Research: Atmospheres*, 114(D8), D00A23. <https://doi.org/10.1029/2008JD010049>.
- Bai, A. J., Liu, C. H., & Liu, X. D. (2008). Diurnal variation of summer rainfall over the Tibetan Plateau and its neighboring regions revealed by TRMM multi-satellite precipitation analysis. *Chinese Journal of Geophysics*, 51(3), 518–529.
- Chang, Y., & Guo, X. (2016). Characteristics of convective cloud and precipitation during summer time at Naqu over Tibetan Plateau. *Chinese Science Bulletin*, 61(15), 1706–1720.
- Chen, B., & Liu, X. (2005). Seasonal migration of cirrus clouds over the Asian Monsoon regions and the Tibetan Plateau

- measured from MODIS/Terra. *Geophysical Research Letters*, 32(1), L01804. <https://doi.org/10.1029/2004GL020868>.
- Chen, H., Yuan, W., Li, J., & Yu, R. (2012). A possible cause for different diurnal variations of warm season rainfall as shown in station observations and TRMM 3B42 data over the southeastern Tibetan Plateau. *Advances in Atmospheric Sciences*, 29(1), 193–200.
- Fox, N. I., & Illingworth, A. J. (1997). The retrieval of stratocumulus cloud properties by ground-based cloud radar. *Journal of Applied Meteorology*, 36(5), 485–492.
- Fu, Y., Liu, G., Wu, G., Yu, R., Xu, Y., Wang, Y., et al. (2006). Tower mast of precipitation over the central Tibetan Plateau summer. *Geophysical Research Letters*, 33(5), 157–158.
- Fujinami, H., & Yasunari, T. (2001). The seasonal and intraseasonal variability of diurnal cloud activity over the Tibetan Plateau. *Journal of the Meteorological Society of Japan*, 79(6), 1207–1227. (Ser. II).
- He, Q. S., Li, C. C., Ma, J. Z., Wang, H. Q., Shi, G. M., Liang, Z. R., et al. (2013). The properties and formation of cirrus clouds over the Tibetan Plateau based on summertime lidar measurements. *Journal of the Atmospheric Sciences*, 70(3), 901–915.
- Li, L., & Ligeer, D. (2001). Analyses of microphysical features for spring precipitation cloud layers in east of Qinghai. *Plateau Meteorology*, 20(2), 192–196.
- Li, Y., Liu, X., & Chen, B. (2006). Cloud type climatology over the Tibetan Plateau: A comparison of ISCCP and MODIS/TERRA measurements with surface observations. *Geophysical research letters*. <https://doi.org/10.1029/2006gl026890>.
- Li, Y. D., Yun, W., Yang, S., Liang, H., Shouting, G., & Fu, R. (2008). Characteristics of summer convective systems initiated over the Tibetan Plateau. Part I: Origin, track, development, and precipitation. *Journal of Applied Meteorology and Climatology*, 47(10), 2679–2695.
- Liu, L. P., Rongzhong, C., & Xinmin, S. (1999). Summary and preliminary results of cloud and precipitation observation in Qinghai-Xizang Plateau in GAME-TIBET. *Plateau Meteorite*, 18(3), 441–450.
- Liu, L. P., Zheng, J. F., Ruan, Z., Cui, Z. H., Hu, Z. Q., Wu, S. H., et al. (2015). The preliminary analyses of the cloud properties over the Tibetan Plateau from the field experiments in clouds precipitation with the various radar. *Acta Meteorologica Sinica*, 73, 635–647.
- Matrosov, S. Y., Uttal, T., & Hazen, D. A. (2004). Evaluation of radar reflectivity-based estimates of water content in stratiform marine clouds. *Journal of Applied Meteorology*, 43(3), 405–419.
- Qiu, Y., Choularton, T., Crosier, J., & Liu, Z. (2015). Comparison of cloud properties between CloudSat retrievals and airplane measurements in mixed-phase cloud layers of weak convective and stratus clouds. *Advances in Atmospheric Sciences*, 32(12), 1628–1638.
- Qiu, Y., & Lu, C. (2016). Investigating CloudSat Retrievals Sensitivity to Forward Iterative Algorithm Parameters in the Mixed Cloud Layers. *Pure and Applied Geophysics*, 173(9), 3111–3124.
- Sato, T., Yoshikane, T., Satoh, M., Miura, H., & Fujinami, H. (2008). Resolution dependency of the diurnal cycle of convective clouds over the Tibetan Plateau in a mesoscale model. *Journal of the Meteorological Society of Japan*, 86, 17–31. (Ser. II).
- Song, X., Zhai, X., Liu, L., & Wu, S. (2017). Lidar and ceilometer observations and comparisons of atmospheric cloud structure at nagqu of tibetan plateau in 2014 Summer. *Atmosphere*, 8(1), 9. <https://doi.org/10.3390/atmos8010009>.
- Suzuki, K., Nakajima, T. Y., & Stephens, G. L. (2010). Particle growth and drop collection efficiency of warm clouds as inferred from joint CloudSat and MODIS observations. *Journal of the Atmospheric Sciences*, 67(9), 3019–3032.
- Taniguchi, K., & Koike, T. (2008). Seasonal variation of cloud activity and atmospheric profiles over the eastern part of the Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, 113, D10104. <https://doi.org/10.1029/2007JD009321>.
- Wang, C., Shi, H., Hu, H., Wang, Y., & Xi, B. (2015). Properties of cloud and precipitation over the Tibetan Plateau. *Advances in Atmospheric Sciences*, 32(11), 1504–1516.
- Wu, G., Liu, Y., Zhang, Q., Duan, A., Wang, T., Wan, R., et al. (2007). The influence of mechanical and thermal forcing by the Tibetan Plateau on Asian climate. *Journal of Hydrometeorology*, 8(4), 770–789.
- Yanai, M., & Li, C. (1994). Mechanism of heating and the boundary layer over the Tibetan Plateau. *Monthly Weather Review*, 122(2), 305–323.
- Yanai, M., Li, C., & Song, Z. (1992). Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon. *Journal of the Meteorological Society of Japan*, 70(1), 319–351. (Ser. II).
- Yang, K., Koike, T., Fujii, H., Tamura, T., Xu, X., Bian, L., et al. (2004). The daytime evolution of the atmospheric boundary layer and convection over the Tibetan Plateau: observations and simulations. *Journal of the Meteorological Society of Japan*, 82(6), 1777–1792. (Ser. II).
- Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., & Chen, Y. (2014). Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: a review. *Global and Planetary Change*, 112, 79–91.
- You, Q., Jiao, Y., Lin, H., Min, J., Kang, S., Ren, G., et al. (2014). Comparison of NCEP/NCAR and ERA-40 total cloud cover with surface observations over the Tibetan Plateau. *International Journal of Climatology*, 34(8), 2529–2537.
- Zhao, C., Liu, L., Wang, Q., Qiu, Y., Wang, W., Wang, Y., et al. (2016). Toward Understanding the Properties of High Ice Clouds at the Naqu Site on the Tibetan Plateau Using Ground-Based Active Remote Sensing Measurements Obtained during a Short Period in July 2014. *Journal of Applied Meteorology and Climatology*, 55(11), 2493–2507.
- Zhao, C., Liu, L., Wang, Q., Qiu, Y., Wang, Y., & Wu, X. (2017). MMCR-based characteristic properties of non-precipitating cloud liquid droplets at Naqu site over Tibetan Plateau in July 2014. *Atmospheric Research*, 190, 68–76.
- Zhao, Y. F., Wang, D. H., & Yin, J. F. (2014). A study on cloud microphysical characteristics over the Tibetan Plateau using CloudSat data. *Journal of Tropical Meteorology*, 30, 239–248.
- Zhao, C., Xie, S., Klein, S. A., Protat, A., Shupe, M. D., McFarlane, S. A., & Hogan, R. J. (2012). Toward understanding of differences in current cloud retrievals of ARM ground-based measurements. *Journal of Geophysical Research: Atmospheres*, 117, D10206. <https://doi.org/10.1029/2011JD016792>.
- Zhao, P., Xu, X., Chen, F., Guo, X., Zheng, X., Liu, L., et al. (2018). The Third Atmospheric Scientific Experiment for Understanding the Earth-Atmosphere Coupled System over the Tibetan Plateau and Its Effects. *Bulletin of the American Meteorological Society*, 99(4), 757–776.