Large-Scale Circulation Environment and Microphysical Characteristics of the Cloud Systems Over the Tibetan Plateau in Boreal Summer

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Abstract The Tibetan Plateau (TP) experiences a particular dynamical and thermal environment due to its unique topography, which could affect the generation and development of its cloud and precipitation. Statistical results of 52-year daily precipitation (1961 to 2012) show that the most frequent daily precipitation is about 3 mm day⁻¹ over the eastern TP (ETP) in the warm season while it is less than 1 mm day⁻¹ over the western TP (WTP). Circulation patterns for rainy and rainless conditions over both the ETP and WTP are investigated. The results show that the rainy weather over the TP is usually related to the moisture transported from the warm ocean by the southerly flow. Moreover, rainy weather in WTP can only appear when the strong southerly flow prevails over the Indian subcontinent. When the south flow is weak, the rainy weather can still develop in ETP under favorable conditions due to the local madid environment. CloudSat observations show that the strong convective system can extend to a level as high as 16 km above the sea level with a favorable dynamical and thermal environment. However, the depth of most precipitating convective clouds over the TP is in a range of 6–9 km. Due to the wetter condition, the precipitating convective clouds over the TP experiences a particular dynamical and thermal environment due to its unique topography, which could affect the generation and development of its cloud and precipitation.

1. Introduction

The Tibetan Plateau (TP), an elevated and expansive highland in the central Asia, stretches about 1,000 km along latitude and 2,500 km along longitude. It is the highest plateau in the world with an average elevation exceeding 4,000 m above the sea level (ASL) and an area of around 2.5 × 10⁶ km². Therefore, the TP is often called as the third pole of the world. Because of the mechanical blockage effects on the westerly jets and strong thermal influence on the atmosphere, the TP imposes significant impacts on the onset and maintenance of East Asia Monsoon, and the weather and climate of downstream (e.g., Chen & Bordoni, 2014; Wen et al., 2014; Wu et al., 2012). These topographical and thermodynamic features make peculiar conditions for the generation and development of cloud and precipitation, which can modulate the energy budget and atmospheric vertical structure through the heating and moistening effects (e.g., Luo & Yanai, 1984; Wang et al., 2019). Moreover, cloud and precipitation are important players in the mechanism that how the TP affects the downstream weather and climate. Therefore, the knowledge of clouds under the peculiar environment (e.g., local thermal heating, different patterns of wind and moisture fields) of the TP could be benefit for understanding the role of the TP in the weather and climate systems.

The TP is a huge heat source in warm seasons and results in vigorous convective clouds systems (e.g., Ge et al., 2019; Luo & Yanai, 1984; Wu et al., 2017). Convective clouds, especially the deep convections (DCs), can lead to heavy rainfall events and play an important role in the local energy and water cycle. The strong vertical transport by DCs over the TP is believed to be a non-negligible player in the decreasing trend in stratospheric ozone during 1980s (Holtslag & Moeng, 1991) and the increasing trend in stratospheric water vapor during 1990s (Stephens et al., 2002), which can magnify warming effects of the greenhouse gas. However, it is reported that the simulated basic climate elements (e.g., temperature and precipitation) still show significant biases over the TP (Xu et al., 2014). An important reason for the bias is the desired
knowledge for the cloud and precipitation over the TP, especially for convective clouds. According to previous studies with the CloudSat product (e.g., Luo et al., 2010), the DC over the TP is shallower than that in the southern Asian monsoon region. For example, the precipitation radar observations from the Tropical Rainfall Measuring Mission (TRMM) show that convection over the TP is 5 and 2 km shallower than that over the land and ocean, respectively (Fu et al., 2008). The CloudSat data set also suggests that the mixed-phase clouds dominate more than 30% over the TP, and the largest occurrences of cloud top height over the TP is about 4 km lower than that over the plain in the East China (Yi, 2019). The vertical structure of cloud amount is characterized by the CloudSat products, and it presents a single peak (located between 7 and 11 km) during January to April and two peaks (located between 5–8 and 11–17 km separately) in the warm season (Yan et al., 2016).

Convective clouds are believed to make great contributions to the summer precipitation. Although DCs over the TP are shallower than that over the flatland, it is still an important type of precipitating clouds and the ice processes are dominant for the rainfall events (Chen & Zhou, 2015; Chen et al., 2017). According to previous studies (e.g., Ge et al., 2019; Jiang et al., 2016; Luo & Yanai, 1984), the TP experiences a strong thermal driving force due to the strong surface heat flux, which makes a favorable environment for the trigger of convections or cumulus. Li and Zhang (2016) used the fine-resolution CloudSat-CALIPSO product to characterize cumulus and found that cumulus is one of the dominant cloud types over the TP in the northern summer. Recent observations revealed that the raindrop size distribution over the TP is broader than over the plain at the same latitude during the warm season (Chang & Guo, 2016). The ground-based radar observations discovered that the DC can extend to as high as 16 km ASL over the Nagchu (a ground station located in the east TP) (Liu et al., 2015). However, the rainfall usually lasts for a short time and the intensity is weak (Chang & Guo, 2016). The TRMM observation reveals that the DCs over the TP has an eastward moving tendency and is a relatively weak system, which has a rain top (defined as the altitude of the first echo signal greater than 0.4 mm hr\(^{-1}\) detected by the TRMM precipitation radar) over 7.5 km and the echo intensity less than 39 dBZ (Pan & Fu, 2015). The observational analysis and model simulation demonstrate that there is moisture transported from the central eastern India to the southwestern TP (Dong et al., 2016). It is claimed that the hydrometeors and moisture are lifted by convective storms over the central eastern India and the Himalayan foothills and then swept over the southwestern TP by the midtropospheric circulation, which makes great contributions to the summer rainfall over the TP.

In this study, the dynamical environment is analyzed based on the rainfall, which serves to investigate the cloud structures under different circulation patterns over the TP. Moreover, the microphysical characteristics of convective clouds associated with the dynamical patterns are investigated using multiyear satellite observation. The results are conducive to improving the understanding level of cloud systems over the TP and are beneficial to improving the simulations of convective clouds.

2. Data

The CN05 data set (Wu & Gao, 2013) is employed in this study. As described by Wu and Gao (2013), the data set is constructed using the “anomaly approach” in the interpolation of about 2,400 station observations in China. More detailed information about this data set can refer to Wu and Gao (2013). Comparing with other data sets (e.g., the data set product from Asian Precipitation—Highly Resolved Observational Data Integration Towards Evaluation of Water Resources), the density of stations over the TP is unprecedented and the data quality over the TP is prodigiously improved, especially in eastern TP (ETP; 30°–37°N, 90°–100°E). Also, it should be aware that the site density in the western TP is still low and this may introduce some uncertainties in the statistics of precipitation. This data set has been widely used to assess the model simulations and study the precipitation climatology over the TP (Xu et al., 2018; You et al., 2015; Zhou et al., 2014). Meanwhile, previous studies have shown different features of apparent heat source and moisture sink between the west TP (WTP) and ETP (e.g., Chen et al., 2017, 2019). Moreover, there are differences in the land cover between the ETP and the WTP (e.g., Cui & Graf, 2009), which can influence the surface fluxes (e.g., sensible and latent heat) and then the cloud and precipitation. Therefore, the TP is divided into the WTP and ETP in this study (Figure 1a). Reanalysis data sets are widely used to analyze the patterns of the large-scale circulation. According to the study (Bao & Zhang, 2013), interim European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-Interim) has a better preference in the mean...
relative humidity. Therefore, the large-scale circulation is investigated by employing ERA-Interim reanalysis with a $1 \times 1^\circ$ resolution.

Currently, the satellite-based approaches are highly effective and convenient methods to explore global cloud systems. Usually, passive satellite sensors can only observe cloud properties of integrated paths or near cloud tops. But, satellite-borne active sensors can detect the vertical distributions and internal structures of cloud optical properties, which can be used to provide more insights into cloud microphysical properties. CloudSat is a National Aeronautics and Space Administration Earth Sciences Systems Pathfinder mission (Stephens et al., 2002), which orbits at 705-km altitude, 98° inclination, and equatorial crossing time of 1:30 a.m./p.m. local time. The primary loaded instrument is the Cloud Profiling Radar, a 94 GHz radar with a 1.1-km-wide effective footprint and 480-m vertical resolution, oversampled to create a 240-m effective vertical resolution. Different patterns of the dynamical environment (e.g., convergence due to inhomogeneous heating or complex terrain and upward motion by the front system) could lead to different types of clouds, which would show differences in microphysical properties and result in quite different cloud radiative effects. In this study, the cloud type products are taken from the 2B-CLDCLASS-lidar data set, which classifies clouds into either stratus (St), stratus (Sc), cumulus (Cu, including cumulus congestus), nimbostratus (Ns), altocumulus (Ac), altostratus (As), deep convective (cumulonimbus), or high (cirrus and cirrostratus) clouds. The classification algorithm is based on different rules for hydrometeor vertical and horizontal

**Figure 1.** (a) Spatial distribution of the multiyear-averaged daily precipitation of MJJAS; the selected regions of the ETP and WTP are marked by red boxes, and the elevation of 3,000 m above sea level is contoured in brown line. (b) The area-averaged daily precipitation (mm day$^{-1}$) in ETP (blue dotted) and WTP (red dotted) for 1961–2012. The horizontal lines are the value of avg + st, where avg and st are the multiyear-averaged precipitation of MJJAS and standard deviation, respectively. The histogram in the upper panel in (b) is the mean monthly precipitation and the histogram in the left panel in (b) is the probability distribution (PD) of the domain-averaged daily precipitation for ETP (blue) and WTP (red).
scales, the maximum effective radar reflectivity factor measured by the Cloud Profiling Radar, indications of precipitation, and ancillary data including predicted European Centre for Medium-Range Weather Forecasts temperature profiles and surface topography height (Saseen and Wang 2008). Taking advantage of more complete cloud vertical structure from lidar and radar measurements, 2B-CLDCLASS-lidar not only improved overall cloud detection but also provided more reliable information for cloud type characterization (Sassen et al., 2008). For more detailed information about the algorithm of the CloudSat data set, refer to Mace (2004) and Wang et al. (2007). The satellite data set would drop its data confidence due to the complex topography over the TP. Therefore, statistics of cloud profiles are conducted to improve the reliability of analysis over the TP for the warm period (May–September, MJJAS) from 2006 to 2014 except year 2011 when no valid data are available.

### 3. Results

#### 3.1. Precipitation and Circulation Patterns

Usually, the extreme rainfall is consequences of the strong convective cloud systems under the favorable circulation patterns. It is found that the TP is a great heat source due to the strong surface heat flux in boreal summer, resulting in frequent and flourishing convective clouds as reported by many studies (e.g., Luo & Yanai, 1984; Wang et al., 2019; Xie & Wang, 2018). Figure 1 shows the precipitation statistical results from 1961 to 2012 for the ETP and WTP. It shows that the precipitation mostly occurs during the monsoon period (MJJAS). The rainfall of MJJAS can account for 59% and 67% of the annual amount of precipitation for the ETP and WTP, respectively. As shown in Figure 1a, the ETP experiences rainier summer than the WTP and the rainiest regions over the TP is the southeast ETP (Figure 1a). Strong rainfall event can exceed 8 mm day$^{-1}$ over the ETP, while only a few days’ precipitation can be larger than 6 mm day$^{-1}$ over the WTP (Figure 1b). These characteristics are largely reflected in the probability distributions (PDs) of daily mean precipitation as shown in the left panel of Figure 1b. The PD shows a peak around 1 mm day$^{-1}$ over the WTP. This peak can be over 10%, and it declines sharply along with the increase of precipitation over the WTP. This PD distribution implies that most rainfall is light and the precipitation capacity of convections is weak over the WTP. However, the shape of the precipitation PD shows a gradual characteristic over the ETP, displaying a peak around 3 mm day$^{-1}$ and decreasing by degrees. In addition, the peak PD over the ETP is about 5%, which is just half of that over the WTP. This suggests that there are more convections and greater precipitation capacity over the ETP than WTP.

Extreme rainfall events usually require the sufficient moisture supply, which is related to the favorable large-scale circulation. Here, the rainy weather is defined as the daily rainfall is one standard deviations (std) greater than the multiyear daily mean (avg) of MJJAS (the dots above two horizontal lines in Figure 1). Based on this criterion, 1,335 and 1,269 events are filtered out for the ETP and WTP during the MJJAS from 1961 to 2012, respectively. A day with precipitation smaller than avg-std is regarded as the rainless day in each region. Any other situation with a daily mean precipitation in range of avg-std to avg + std is regarded as normal condition. Based on these definitions, six circumstances are classified in Table 1. In Case1, both the ETP and WTP are rainy, Case2 both ETP and WTP are rainless, Case3 WTP is rainy and ETP is rainless or normal, Case4 WTP is rainless and ETP is rainy or normal, Case5 ETP is rainy and WTP is rainless or normal, and Case6 ETP is rainless and WTP is rainy or normal. Then, the large-scale circulation patterns and the moisture condition are investigated based on these categories over both ETP and WTP. The environmental characteristics of the rainy weather for the entire TP can be investigated by comparing Case1 with Case2. Previous studies have indicated that the moisture source for the ETP precipitation is different from the WTP under certain situations (Ueda et al., 2003; Zhang et al., 2016). The particular dynamical and moisture conditions for the rainy WTP can be detected via the comparison between Case3 and Case4, and conditions for ETP can be investigated by the comparison between Case5 and Case6.

Figure 2 shows the differences in the large-scale circulation and moisture condition between the rainy and rainless conditions for different categories (Table 1). When the entire TP experiences rainy weather, the southerly wind is intensive and the atmosphere is much moister at 850 hPa (Figure 2a). Moisture will be

| Table 1 |
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| **Classification Categories Based on the Mean Daily Precipitation and Standard Deviation** |
| **Circumstance** | **Description** |
| Case1 | Both the ETP and WTP experience rainy weather. |
| Case2 | Both the ETP and WTP experience rainless weather. |
| Case3 | The WTP is rainy, and the ETP is rainless or normal. |
| Case4 | The WTP is rainless, and the ETP is rainy or normal. |
| Case5 | The WTP is rainy, and the WTP is rainless or normal. |
| Case6 | The ETP is rainy, and the WTP is rainless or normal. |
transported from the south to the TP by the south flow. This provides a necessary moisture condition for the rainfall, which is also indicated by previous studies (e.g., Chen et al., 2017; Xu et al., 2014). Comparing with Case1, Case2 shows a dryer atmosphere over the ocean and a wetter atmosphere over the land (figure not

Figure 2. Differences in the large-scale circulation and moisture between Case1 and Case2, Case3 and Case4, and Case5 and Case6 at (a, c, and e) 850 and (b, d, and f) 500 hPa.
shown), which implies that the moisture transport from the ocean to the land is more active. Meanwhile, the circulation difference at 500 hPa between the rainy and rainless weather shows a cyclonic pattern with a center located around 19°N and 78°E (Figure 2b). Additionally, there is intensive southerly wind component at the east edge of the cyclonic center (89°E and 20°–25°N), and there is intensive southerly wind component at around 87–100°E and 27°N (Figure 2b). This means that the vertical motion is more intense over the Indian subcontinent when the entire TP is rainy. This vertical movement lifts more ocean-evaporated vapor to the high level, and the vapor is then transported to the TP by the southerly airflow. This vapor transport hypothesis agrees with the study of Dong et al. (2016).

When these two opposite weather cases of rainy and rainless occur in WTP, the circulation pattern differences are shown in Figures 2c and 2d. The 850-hPa wind field difference shows that the southerly wind component of Case3 is more intense than Case4, which is similar to the difference between Case1 and Case2 (Figures 2a and 2c). Analogously, the circulation difference between Case3 and Case4 has a cyclonic pattern at 500 hPa (Figure 2d), which is similar to the situation of the entire TP (Case1 and Case2). When only WTP is rainy, the cyclonic center locates at around 19°N and 73°E (Figure 2c), which is on the western side of the cyclonic center in Figure 2b. It shows that the southerly wind component is intensive at the cyclonic center’s eastern edge (78°–83°E and 20°N, Figure 2d). Also, the southerly wind component slight increases in the region of 20°–30°N and 78°–83°E. This will make positive effects on the moisture transport between the south and WTP. Meanwhile, it is noticed that there is a convergence tendency at around 80°E and 30°N (Figure 2d), where is the WTP’s south foothill. This convergence could be beneficial for the moisture’s climbing the upslope and transporting to the WTP, which could make great positive impacts on the trigger of deep cloud systems and heavy rainfall in WTP (Chen et al., 2019).

Figures 2e and 2f show the differences in the large-scale circulation and the moisture field between Case5 and Case6, which represent that the ETP experiences rainy and rainless weather, respectively. The 850-hPa moisture difference between Case5 and Case6 is mostly less than 2.0 g kg$^{-1}$ (Figure 2e), which is much less than the difference between Case1 and Case2, or Case3 and Case4 (Figures 2a and 2c). Also, the difference in the 850-hPa southerly wind strength between Case5 and Case6 is much weaker than the difference between Case1 and Case2, or Case3 and Case4 (Figures 2a and 2c). At 500 hPa, the maximum difference in the moisture between Case5 and Case6 appears over the ETP with a maximum value less than 1.5 g kg$^{-1}$ (Figure 2f). However, the maximum 500-hPa moisture difference between Case1 and Case2, or Case3 and Case4, can be as large as 1.8 g kg$^{-1}$ (Figures 2b and 2d). Moreover, the coverage with differences greater than 1.6 g kg$^{-1}$ can extend to the most part of TP and the southern part of the India Peninsula. Furthermore, there is a cyclonic pattern in the wind field difference between the rainy and rainless conditions in ETP, and the core of this cyclone locates at 94°E and 31°N (Figure 2f), implying that stronger upward motion is stronger in the rainy situation than the rainless condition in ETP. Under this situation, the local moisture source is the major contributor for the ETP precipitation, which is benefited from the local humid environment and strong heating effects due to the surface heat fluxes. In contrast, this situation does not happen over WTP because of the dry atmosphere. This is supported by Chen et al. (2019) who found that the WTP heavy precipitation shows great dependency on the moisture transported from the south.

3.2. Clouds Over the TP

Differences in the large-scale circulation patterns and moisture condition will arouse different kinds of clouds. Here, the CloudSat cloud product is employed to investigate the cloud properties over the TP. Considering the great differences in coverage area between the CloudSat and CN05 precipitation data set, the weather classification is based on the in-cloud water phase state detected by the CloudSat, which includes no rain, drizzle, and rainy (both liquid and solid). Figures 3 and 4 show frequencies of different cloud types in MJJAS for the ETP and WTP, respectively. Generally, nimbostratus (Ns), DC, altostratus (As), altocumulus (Ac), cirrus (Cr), stratocumulus (Sc), and cumulus (Cu) are the main cloud types over the TP during the warm season. Typically, DC becomes active in June and achieve its maximum exuberant period in July and August, which can be over 15% of the total cloud. Then, it shrinks rapidly to 5% in September. Another notable characteristic is that the total frequency of two major precipitating cloud types (DC and Ns) is 40% over the TP with unapparent inter-seasonal variations (Figures 3a and 4a), and these two cloud types can account around 80% of the total clouds in rainy condition (Figures 3d and 4d).
Figure 3. Frequencies (%) of nimbostratus (Ns), deep convection (DC), altostratus (As), altocumulus (Ac), cirrus (Cr), stratocumulus (Sc), stratiform (St), and cumulus (Cu) in May, June, July, August, and September under (d) rainy (Liquid+Solid), (c) drizzle (Drizzle), (b) no rain (NoRain), and the (a) whole period (All the condition) in ETP.

Figure 4. Same as Figure 3 but for WTP.
As denoted by previous studies (e.g., Chen et al., 2015), DC is an important type of precipitating clouds over the TP. This is also identified by the CloudSat observation as shown in Figures 3 and 4, especially in July and August. The precipitation mostly occurs in June, July, August, and September over the TP (Figure 1). The rainiest month is July, which is also the month with the most convections (Figures 3a and 4a). This indicates that convection is largely responsible for the total precipitation in the midsummer. However, the convective clouds rapidly decreased in September (Figures 3a and 4a) while the TP precipitation does not changes dramatically (Figure 1), implying that Ns become a major contributor to the precipitation during this period. This characteristic can be seen in Figures 3d and 4d, which shows that there is high frequency of Ns during the rainy period in September. Analogously, the similar situation is obtained in May.

Surface heat fluxes are important driving forcing for the cumuliform cloud’s trigger, especially for the TP (Chen et al., 2019; Chen & Avisser, 1994). When the warm season comes, the intensive surface heat fluxes will make positive effects on the triggers and development of cumuliform clouds. As a result, altocumulus and cumulus become active in early summer (June, Figures 3a and 4a). However, DC is still in inactive during this period. Usually, altocumulus and cumulus are not deep cloud systems and produce little precipitation. Therefore, altocumulus is prevalent in summer when it is not rainy (Figures 3b and 4b). Cumuliform cloud is promoted by the intensive surface thermal forcing in midsummer. DC becomes active in midsummer (Figures 3a and 4a) and the precipitation increases (Figure 1). In addition, there is little altocumulus during the rainy weather over the TP (Figures 3d and 4d). When there is no rain, altostratus is the dominant cloud (Figures 3b and 4b). The sky is dominated by stratocumulus in a drizzle day. Generally, shallow cumuliform clouds (including altocumulus, cumulus, and stratocumulus) account more than one-third cloud cover in summer (June, July, and August, Figures 3a and 4d). However, these clouds make little contribution to the precipitation (Figures 3d and 4d). Deep cumuliform cloud (e.g., DC) reaches its most active period in midsummer and can make great contributions to the TP’s precipitation (Figures 1, 3d, and 4d).

### 3.3. Cloud Structures

Figures 5 and 6 show the vertical PD for four major cloud types (nimbostratus, DC, stratocumulus, and cumulus) for the rainy weather over the ETP and WTP, respectively. The stratocumulus and cumulus PDs display a unimodal structure with a sharp peak around 6 km ASL in MJJAS (Figures 5 and 6), which is approximately 1.5 km above the ground level. Stratocumulus has a sharper PD form than cumulus. Stratocumulus is mostly observed below 10 km ASL while cumulus can be found around 12 km ASL. Nimbostratus, which is an important type of precipitating cloud as discussed in previous section, also shows a single-peaked vertical structure in PD and occupies a deeper layer than cumulus and stratocumulus (Figures 5 and 6). DC’s PD displays a trapezoid-like shape. The high frequency of DC usually starts at 6 km ASL and can extends to over 10 km ASL (Figures 5 and 6), which is different from other cloud types. The lowest DC is observed below 5 km ASL over the ETP while it is around 5 km ASL over the WTP. This suggests the DC’s cloud base is higher in WTP than ETP.

Comparing with shallow clouds, precipitating clouds (nimbostratus and DC) become more and more active from May to August (Figures 5 and 6). Nimbostratus cannot develop over 15 km ASL in May but can break through 15 km ASL in midsummer (Figures 5 and 6). The nimbostratus’ PD extends to higher altitude in ETP than WTP in MJJAS (Figures 5 and 6), which means that nimbostratus can develop deeper in ETP due to its humid environment. The highest altitude of DC is around 13 km ASL in May and 15 km ASL in June and can develop higher than 15 km ASL in July and August in ETP and WTP. Usually, the DC has a depth greater than 5 km. Therefore, DC’s PD over 10 km ASL can be approximately regarded as its cloud top. DC will develop higher and deeper along with the increase of the surface heat fluxes from May to August (Figures 5 and 6). When the summer goes, DC becomes weak, indicating the atmosphere conditions (e.g., surface heat fluxes and moisture) become unfriendly to DC.

The products of radar-lidar cloud classification, cloud water content, column-integrated precipitation, and cloud geometrical profile are used to further investigate characteristics of precipitating convective clouds (PCCs). Here, PCC is selected by the following criteria: (1) cloud type of DC is identified in 2B-CLDCLASS-lidar data set and (2) a valid profile is obtained in 2B-CWC-RVOD data set. Since PCC is a part of DC, which may have relative greater precipitating capacity than DC. Figures 7a and 7b show cloud top and cloud base for the ETP and WTP PCC during May to September, respectively. According to the PCC criteria, few samples are filtered out in May and June in WTP; this may be caused by the limited
moisture condition. Therefore, there are no valid data for May and June in WTP (Figure 7). The PCC’s maximum cloud top can be over 16 km ASL in both ETP and WTP (Figures 7a and 7b), which agrees with the ground-based radar observations (e.g., Liu et al., 2015). PCC has its maximum cloud top in July and August in ETP, and it is August in WTP (Figures 7a and 7b). The PCC’s cloud base is around 5 km ASL, which confirms the Cloud-Resolving Model simulation reported by Chen et al. (2017). Comparing with the WTP cloud, water vapor in ETP can condensate at a lower altitude in August due to the moister environment, resulting in a lower cloud base (Figure 7a). Cloud depth can reflect the cloud precipitation potential capacity and it is shown in Figure 7c. PCC over the TP has a depth in the range of 6–9 km, which is thinner than DCs over the American Southern Great Plains and the tropical ocean (e.g., Wu et al., 2007). The ETP PCC usually has a depth thinner than 8 km in May and June (Figure 7a) and hits its maximum depth in July. As a result, PCC will lead to great precipitation in July, which agrees with monthly averaged precipitation demonstrated in Figure 1b. PCC reaches its highest cloud top (approximately 18 km ASL) in August in WTP, which is even higher than that of ETP (around 17 km ASL, Figures 7a and 7b). The highest cloud top of PCC suggests that the deepest cloud occurs in August in WTP as shown in Figure 7c. Along with the recession of the India Monsoon circulation, PCC’s depth sharply decreases in September in WTP (Figure 7c), which is responsible for the dramatically reduced precipitation in September (Figure 1b). This suggests that the WTP rainy weather shows great dependences on the transported moisture associated with the large-scale circulation pattern.

Figures 8 and 9 show the multiyear monthly averaged profiles of liquid effective radius (Re), ice effective radius (Rei), cloud droplet number concentration (Nc), ice number concentration (Ni), cloud liquid water...
content, and cloud ice water content for PCC in ETP and WTP, respectively. Over the ETP, Re, Nc, and liquid water content have the similar shapes in the vertical structure. Cloud liquid effective radius of PCC is in a range of 5–15 μm and hits its maximum around 8 km ASL. The maximum value is similar to the results

Figure 6. Same as Figure 5 but for WTP.

Figure 7. Averaged (2007–2012) cloud top height and cloud base (dots) height for precipitating convective clouds over the ETP (a) and WTP (b), and the cloud depth of precipitating convective clouds during May to September (c). In panels (a) and (b), horizontal arrows indicate the maximum (right) and minimum (left) cloud base height, and vertical arrows indicate the maximum (up) and minimum (down) cloud top height. The error bar in panel (c) is the standard deviation.
of a mixed-phase boundary layer cloud over the southern Quebec but the minimum value is much smaller than the southern Quebec (Barker et al., 2008). Barker et al. (2008) indicated that CloudSat mostly overestimates cloud liquid effective radius comparing with the airborne observations. Also, it is much smaller than the ground-based observation on the summit of Mount Werner in Colorado (Borys et al., 2000) and is much smaller than DCs over 30°S to 30°N sampled by MODIS (Young et al., 2013). The altitude of the maximum cloud liquid effective radius is higher in July and August than other month (Figure 8a), which is consistent with the analysis of the rainfall and the cloud depth. The ice crystal appears at around 5 km ASL in ETP and has a maximum value at around 6 km. It is noticed that levels of maximum ice water content and Ni in May are much lower than other month. This result implies that PCC is not vigorous in May in ETP, which agrees with the analysis of the cloud depth (Figure 7) and precipitation (Figure 1). The WTP PCC structure is very similar to that over ETP except that the cloud droplet appears at a lower level in July (Figures 9a, 9c, and 9e), implying PCC can develop at a lower altitude, which agrees with the analysis of cloud base shown in Figure 7b. Most of PCCs have a cloud ice

Figure 8. Monthly averaged profiles of liquid effective radius (a), ice effective radius (b), cloud droplet number concentration (c), ice number concentration (d), cloud water content (e), and ice water content (f) for precipitating convective cloud in ETP. The error bar is the standard deviation.
number concentration below 200 L−1 and a cloud droplet number concentration smaller than 100 cm−3. These values are much smaller than results of Mount Werner in Colorado (Borys et al., 2000) and Shannxi, China (Dai et al., 2010). Small cloud particles and low number concentration lead to a low level of cloud water content (Figures 8e, 8f, 9e, and 9f), suggesting that the TP PCC is relatively weak in precipitation capacity.

4. Summary and Discussion

Cloud systems over the TP, especially PCCs, are investigated through the analysis of both the circulation patterns and the in-cloud structures detected by CloudSat. Precipitation mostly concentrates in the period of May to September over the TP. The most frequent domain-averaged daily precipitation is about 3 mm day−1 in ETP while it is less than 1 mm day−1 in WTP. The circulation and moisture patterns demonstrate that the 850-hPa southerly wind component is intensive and the air mass over the Indian subcontinent is humid when the TP experiences rainy weather. Comparing to patterns of the rainless weather, the upward motion over the Indian subcontinent is stronger under rainy weather over the TP, and there is a cyclonic
pattern in the 500-hPa wind field differences between the rainy and rainless conditions. When only WTP is rainy while ETP is rainy or normal, the cyclonic pattern in the 500-hPa wind field differences moves westward 1–2°, while the moisture differences between the WTP rainy and not-rainy conditions show similar patterns to the situations of the entire TP. However, when only ETP is rainy, the differences in moisture is smaller than those over the WTP or the entire TP. These results suggest that the strong rain events in WTP show more dependence on the moisture transported from the south.

The analysis of CloudSat products demonstrates that the DCs and nimbostratus are the main precipitating cloud types over the TP. DCs are most vigorous in July and August over the TP, which is largely responsible for the annual rainfall peak in boreal summer. Strong convective systems can develop over 16 km ASL over the TP. However, the depth of most PCCs is in the range of 6–9 km over the TP, and it is deeper in ETP than WTP. Due to the wetter condition, PCC in August can be triggered at lower altitude in ETP than WTP. CloudSat estimates the cloud liquid effective radius of PCC over the TP is in a range of 5–15 μm and achieves its maximum around 8 km ASL. This is a quite small value for deep convective systems. Comparing with other regions, PCC over the TP are characterized by CloudSat with properties of thinner cloud depth and smaller cloud particles, which suggests that the TP PCC holds a weak precipitation capacity. Such characteristics may relate to the local topography and thermal characteristics, and the mechanism among these factors can be investigated via numerical model in the future work.

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